



# ***CLARAty Reusable Robotic Software***

## ***Coupled Layer Architecture for Robotic Autonomy***

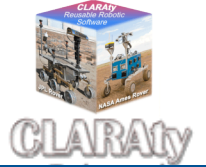
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Group Supervisor, Robotic Software Systems  
Mobility and Robotics Section  
Jet Propulsion Laboratory

and the CLARAty team

Section Seminar  
July 25, 2007



# Presentation Overview



- **Problem Statement**
- **Sample Deployments** (videos)
- **Challenges**
- **Technical Approach**
- **Status**
- **Summary**

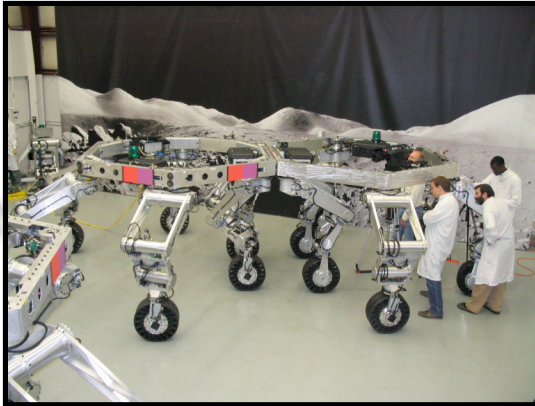


# NASA/JPL Developed Different Rovers

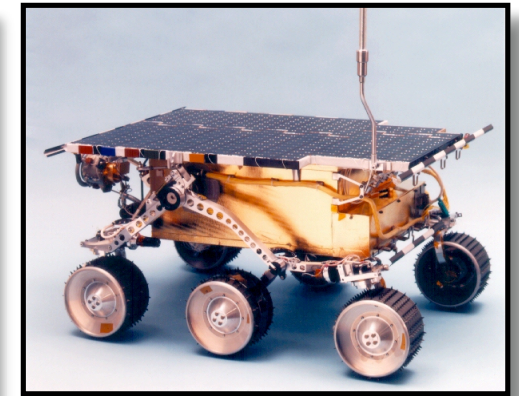
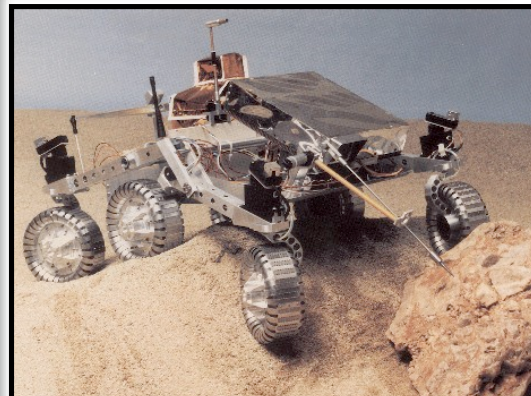


CLARATy

Large



Medium



Small



Research & flight



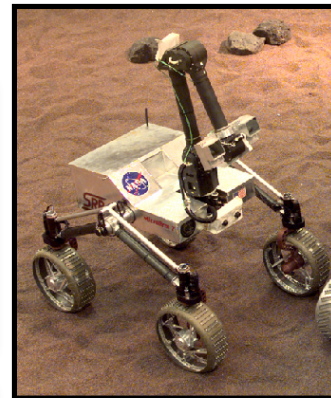


# Different Mobility Mechanisms



CLARAty

- Wheeled vehicles
- Legged vehicles
- Hybrid vehicles
- Different wheel types and configuration







# Problem and Challenges



- Problem:

- Difficult to **share algorithms across projects**
- **Lack of integrated** and **validated** robotic technologies prior to flight infusion
- **Redundant** infrastructure for robotic projects / platforms
- **No framework** to capture technologies from universities and other centers
- **No interoperable** software among robotic platforms (e.g. Rocky 8, FIDO, Rocky 7, K9, K10, ATRV)

- Key Challenges

- Robots have different physical characteristics
- Robots have different hardware architectures
- Contributions made by multiple institutions
- Advanced research requires a flexible framework
- Software must support various platforms
- Lack of a common low-cost robotic platforms
- Software must be unrestricted and accessible (ITAR and IP)
- Software must integrate legacy code bases

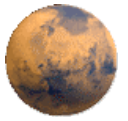


# CLARAty Reusable Robotic Software



- Initiated by the Mars Technology Program (MTP) in 1999 to unify its robotic software developments
- Collaborative effort among **JPL, NASA ARC** and **Carnegie Mellon**
- Supported two rounds of MTP competed research programs
- Supported formal technology validation for MSL Focused Technology Program





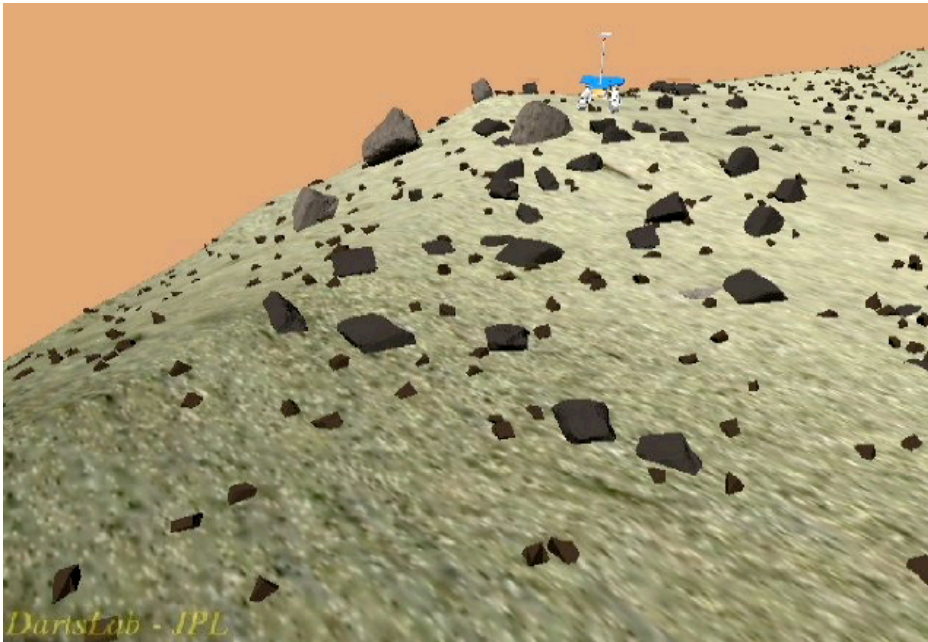
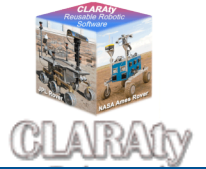
## ***Sample Deployments***

- Navigating in a Simulated Environment
- Navigating Multiple Rovers in Mars Yard
- Autonomous Targeted Driving
- Single-cycle Instrument Placement
- Targeted Driving with MER and MSL algorithms
- Advanced Locomotion and Path Planning

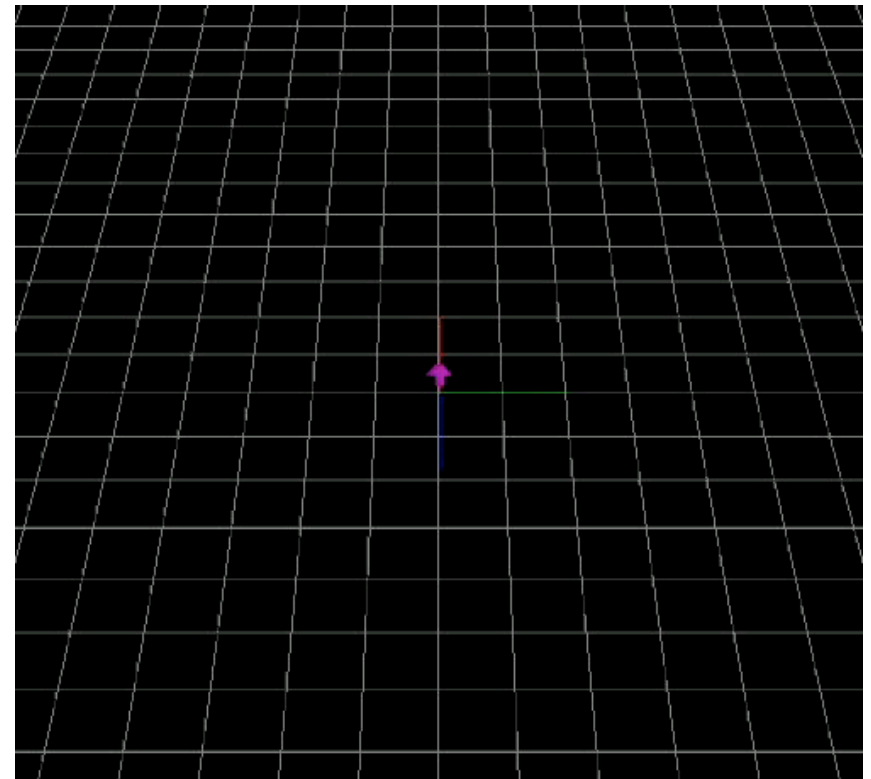




# Navigating in a Simulated Environment

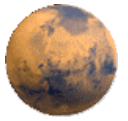


ROAMS



CLARAty Morphin  
Navigator GUI

*Courtesy of SOOPS task*



## ***Sample Deployments***

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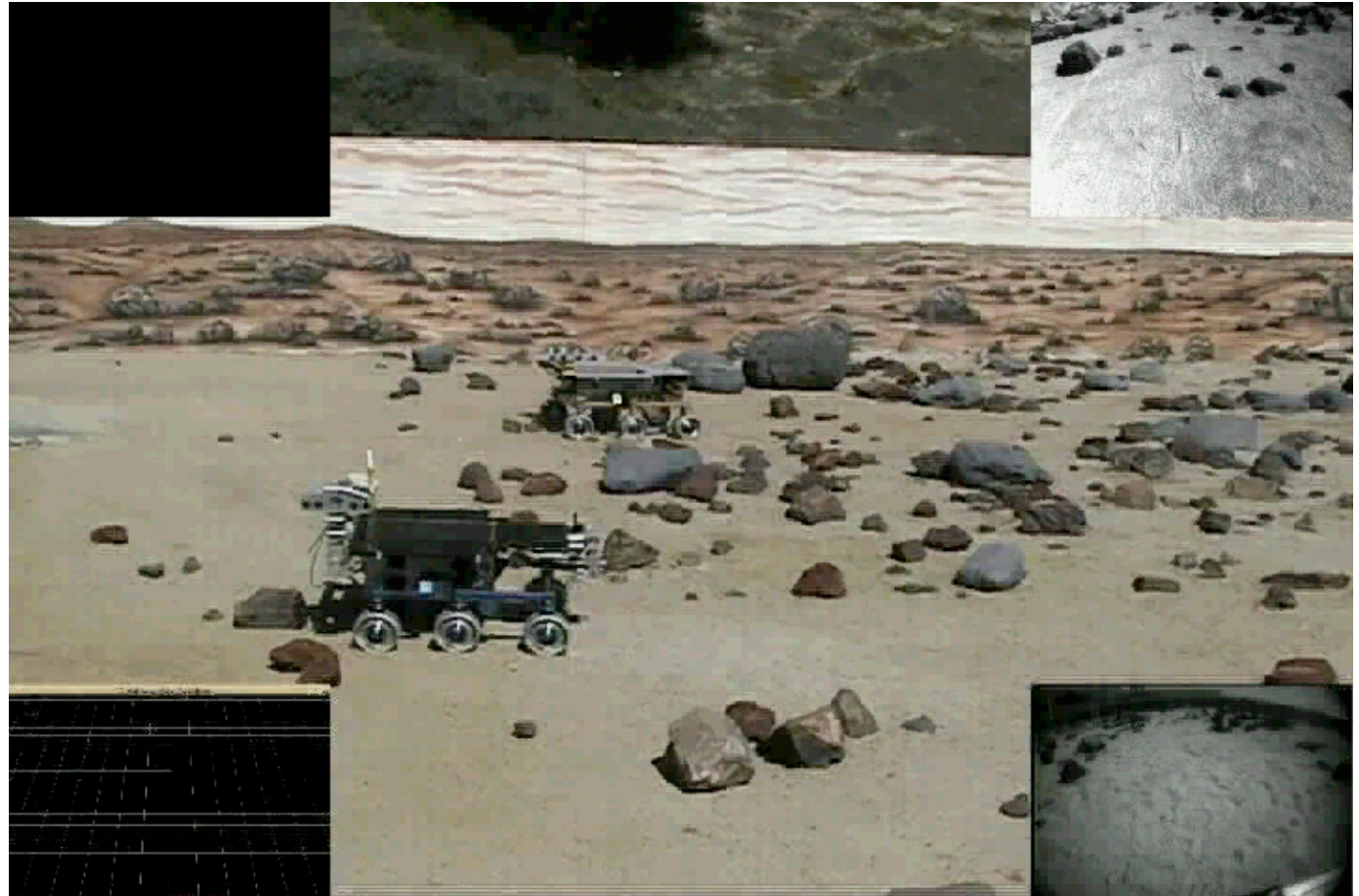


# Navigation with Path Planning on Two Rovers

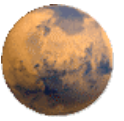


## Complex Algorithms on different Platforms

- I/O, motion control
- Trajectory Generation
- Rough Terrain Locomotion
- Odometry Pose Estimation
- Stereo Processing
- Visual Odometry
- Navigation (Morphin)
  - Obstacle avoidance
  - Path Planning





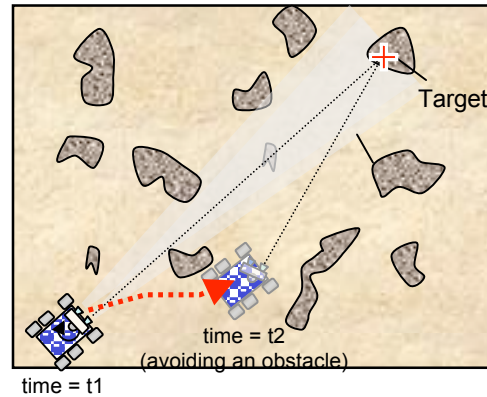


## ***Sample Deployments***

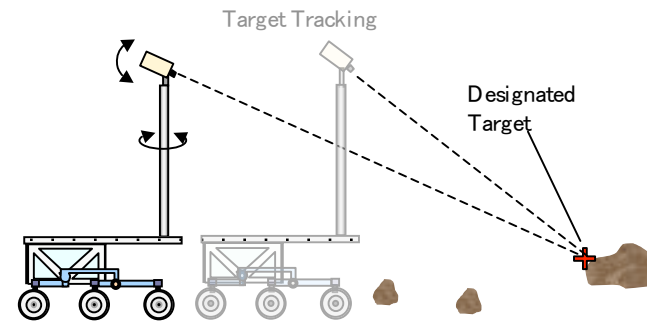
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# Targeted Driving using Visual Tracking



(a)



(b)



1<sup>st</sup> Frame

Changes in FOV



37<sup>th</sup> Frame after 10 m



# Autonomous Targeted Driving (more difficult terrain)



Uses following technologies:

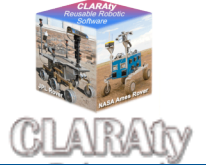
- Visual Target Tracking
  - Falcon or
  - MER VTT
- Navigation with obstacle avoidance
  - Morphin or
  - MER GESTALT
- Pose estimation
  - 6DOF EKF and
  - Visual odometry



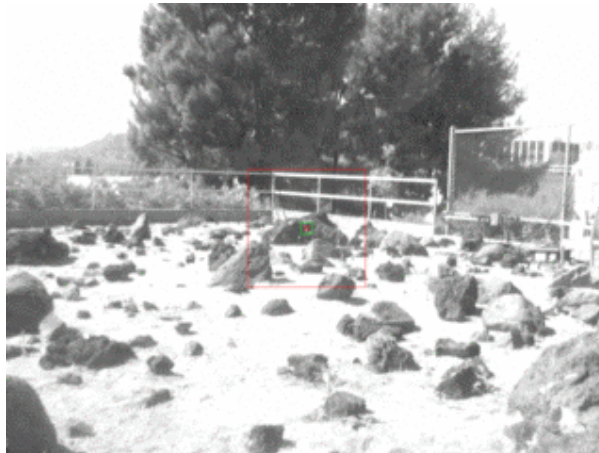




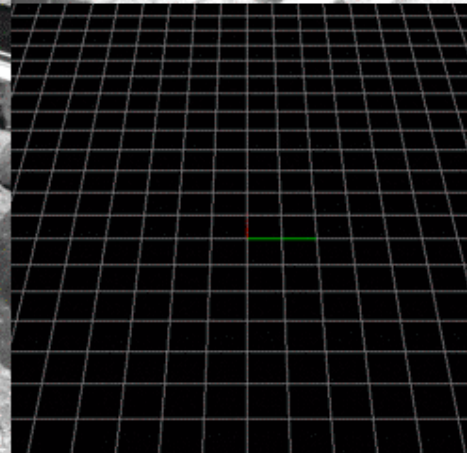
# Autonomous Targeted Driving (more difficult terrain)



VTT Image - navcam



VO Image - navcam



Front Hazcam

Morphin Navigator



## ***Sample Deployments***

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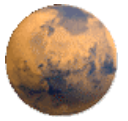
# Integrated Single-Cycle Instrument Placement



CLARAty





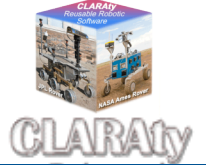


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# Autonomous Targeted Driving



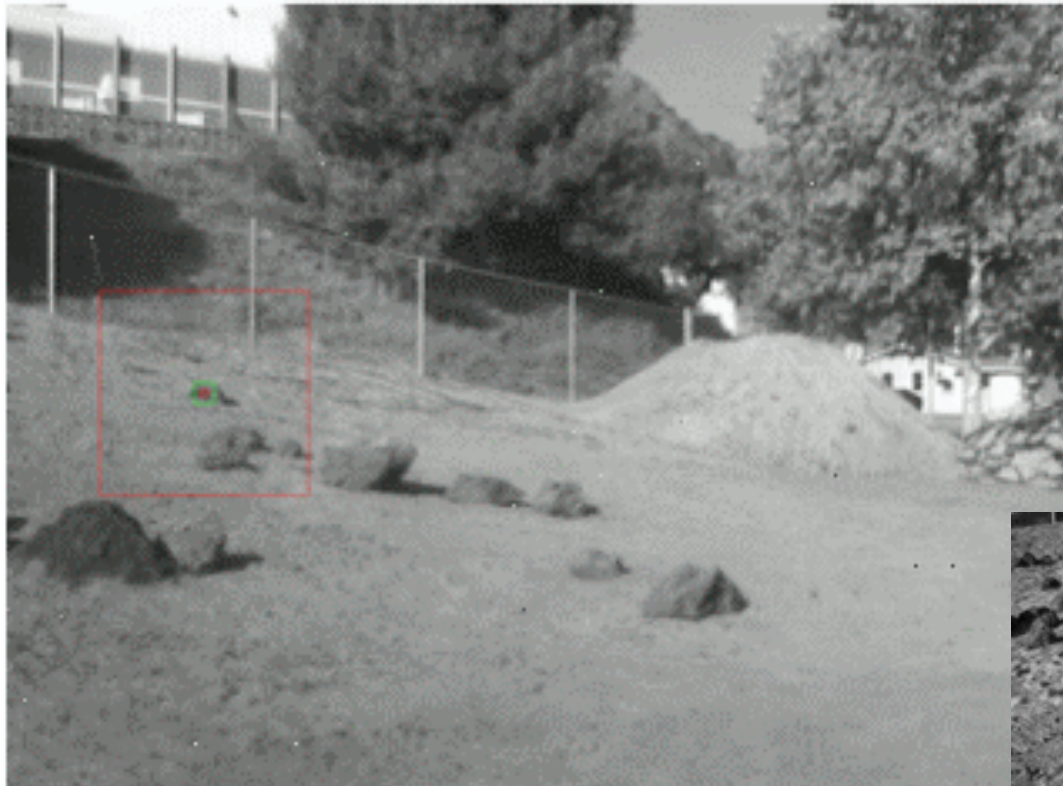
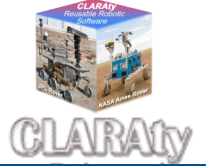
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- Navigation with obstacle avoidance
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- Pose estimation
  - 6DOF EKF or
  - Visual odometry

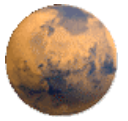




# Autonomous Targeted Driving





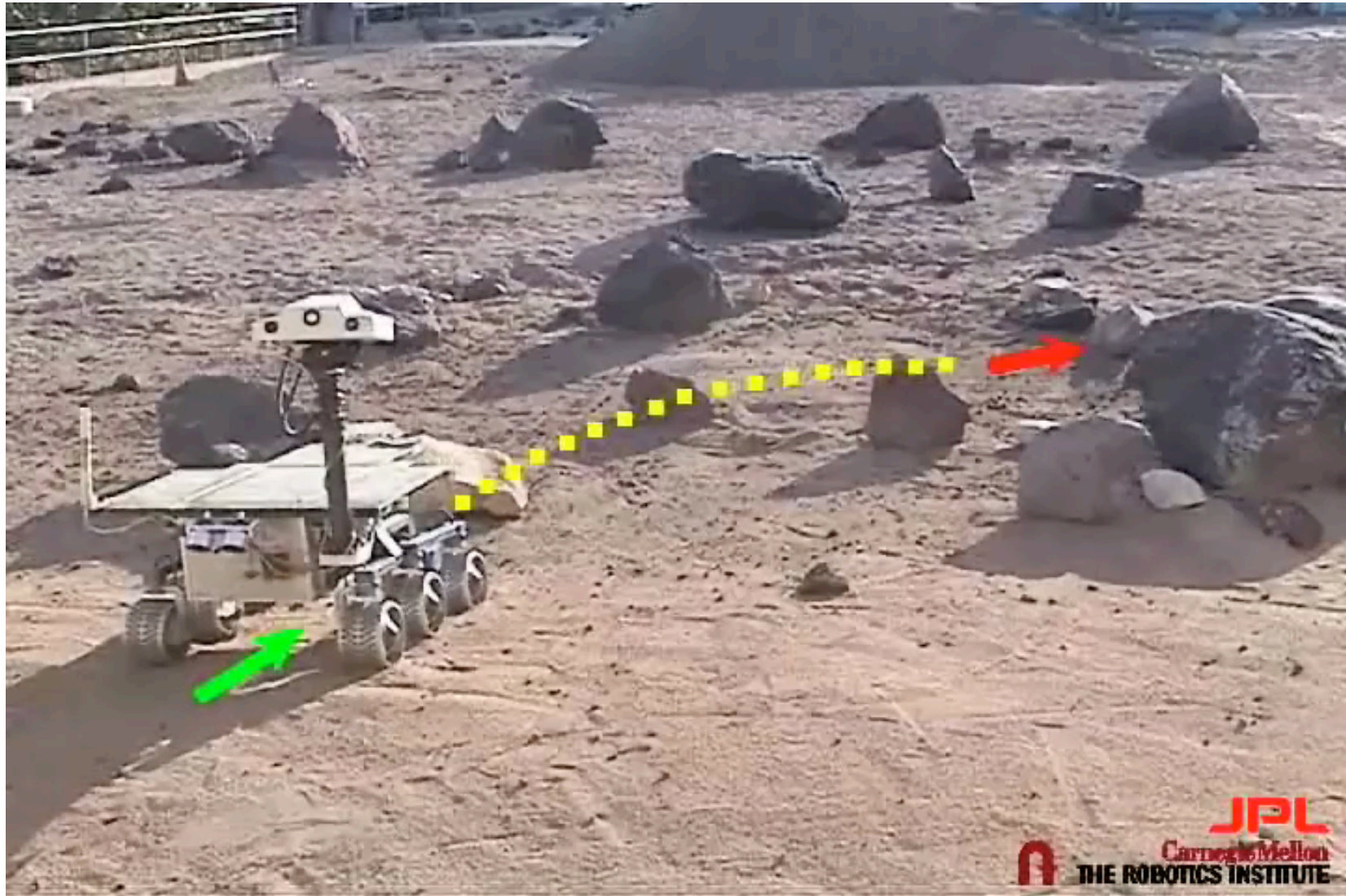
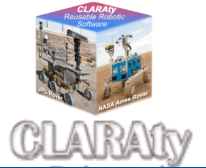


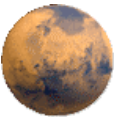
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# Advanced Path Planning and Locomotion





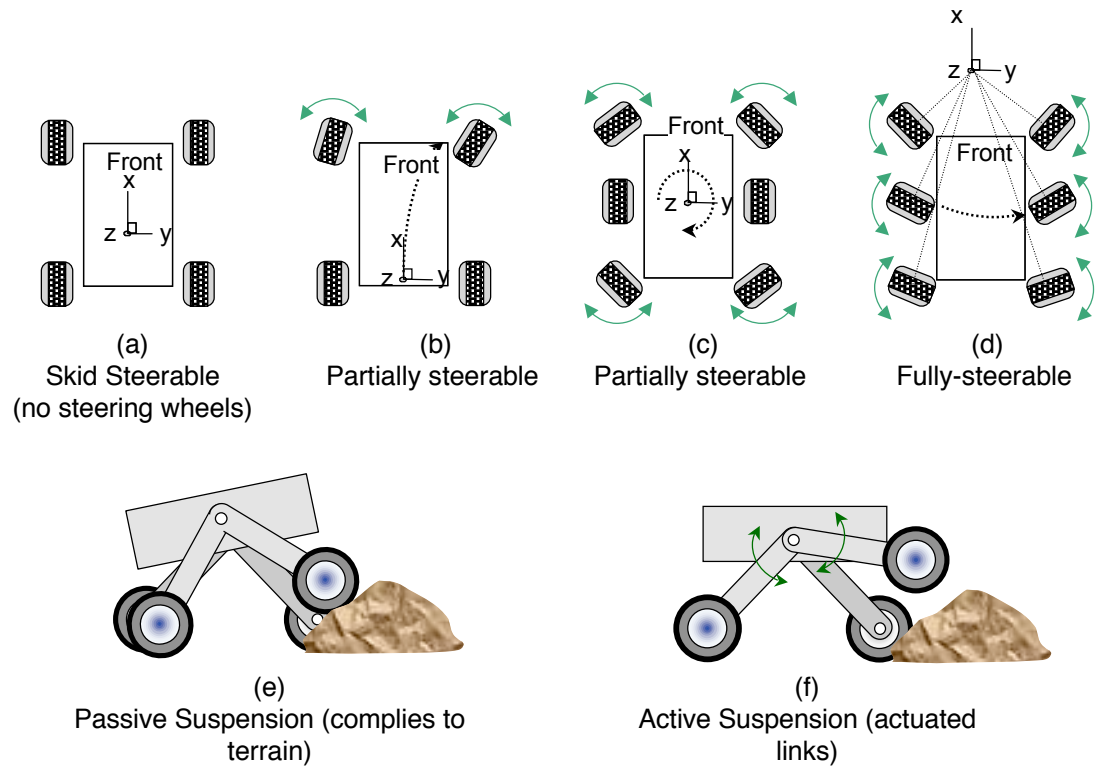
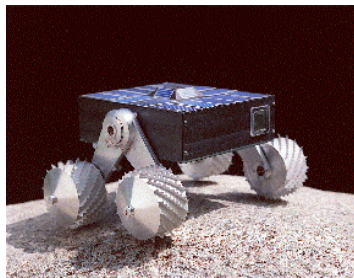
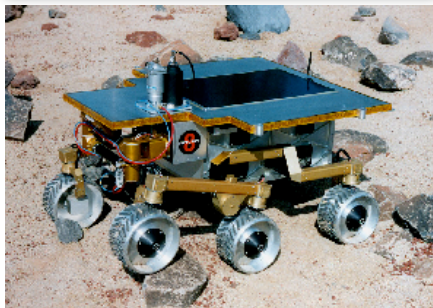
## ***Challenges of Interoperability***

- Mechanisms and Sensors
- Hardware Architecture
- Software Algorithms





# Different Mobility Mechanisms





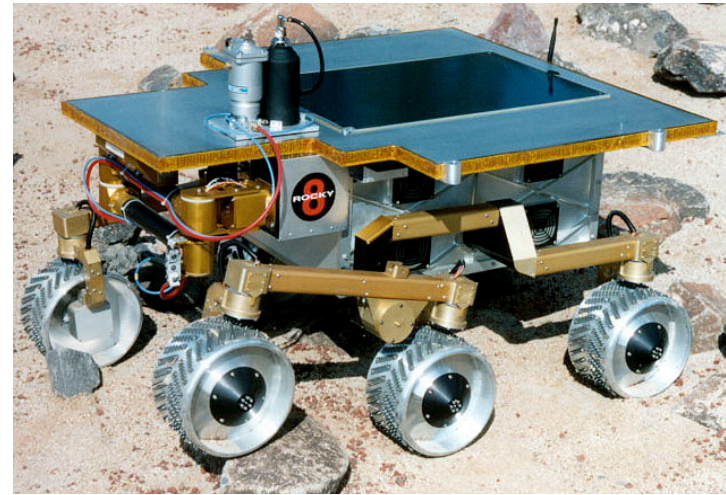
# Have Different Capabilities



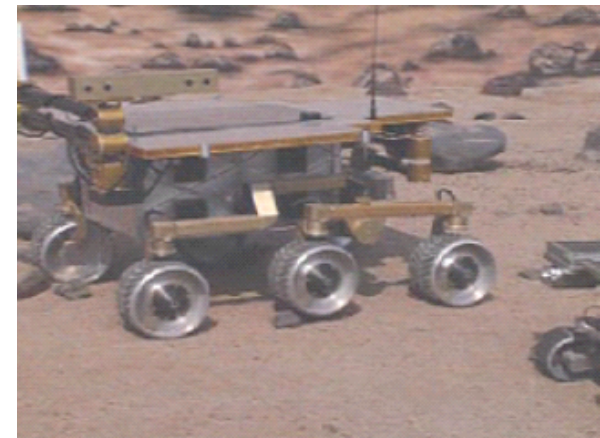
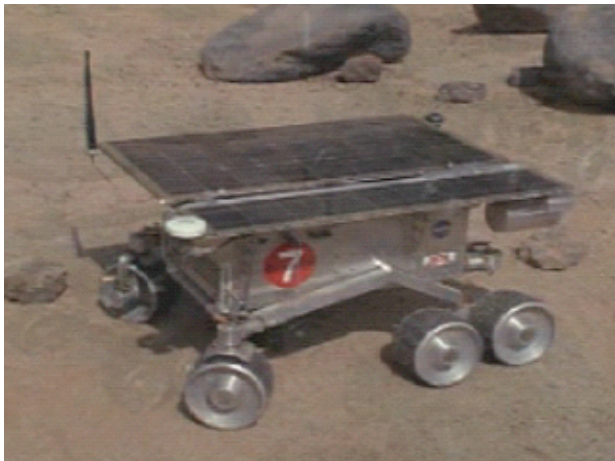
CLARAty



Rocky 7



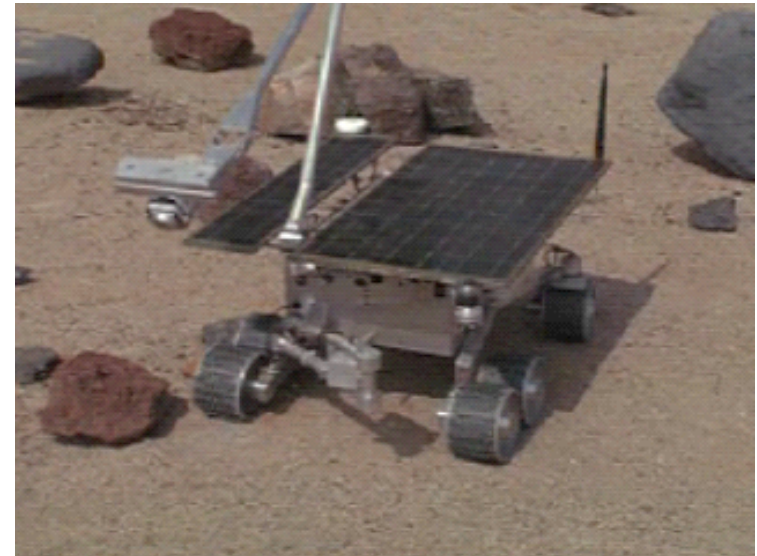
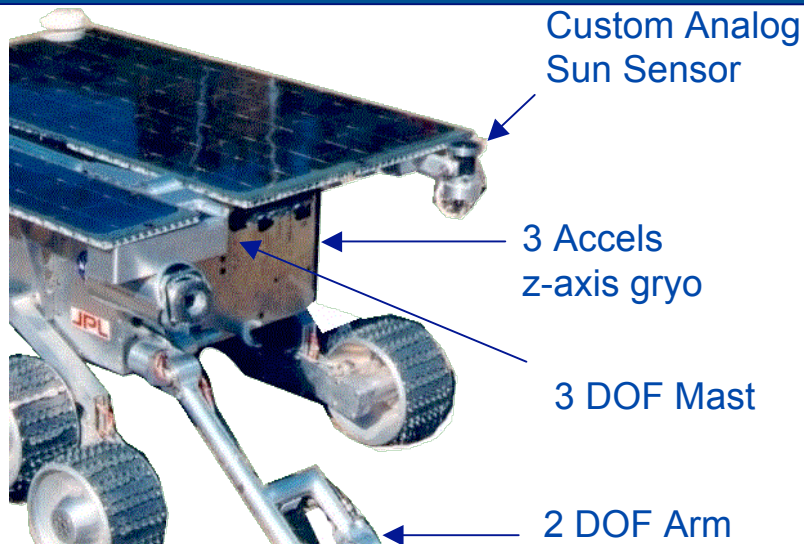
Rocky 8



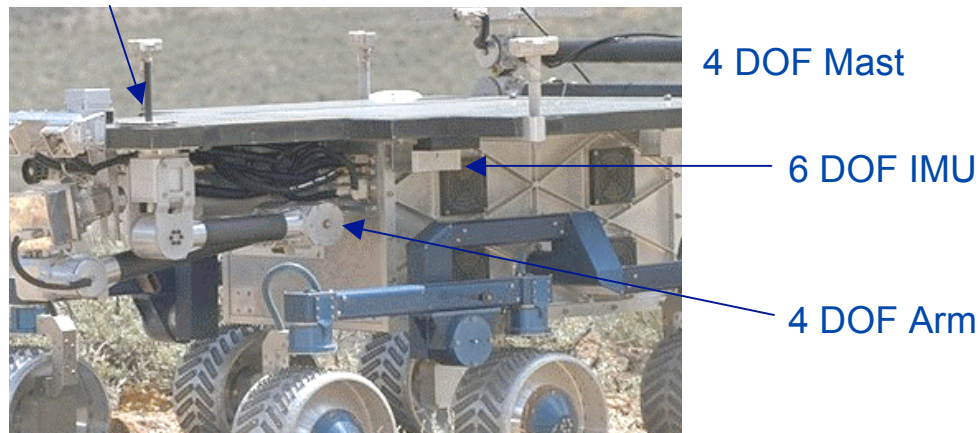




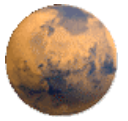
# Different Sensors and Appendages



Camera Sun Sensor





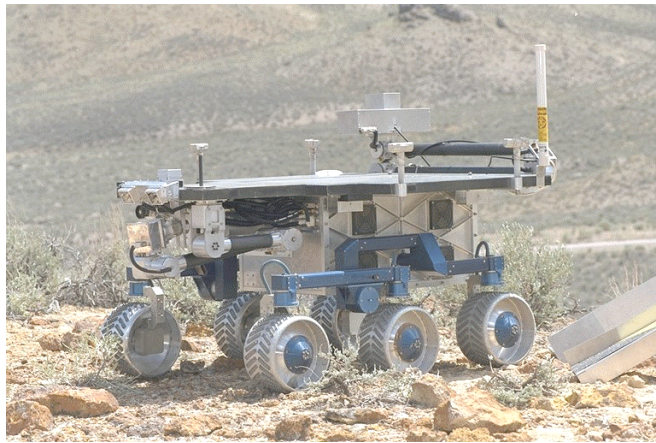


## ***Challenges of Interoperability***

- Mechanisms and Sensors
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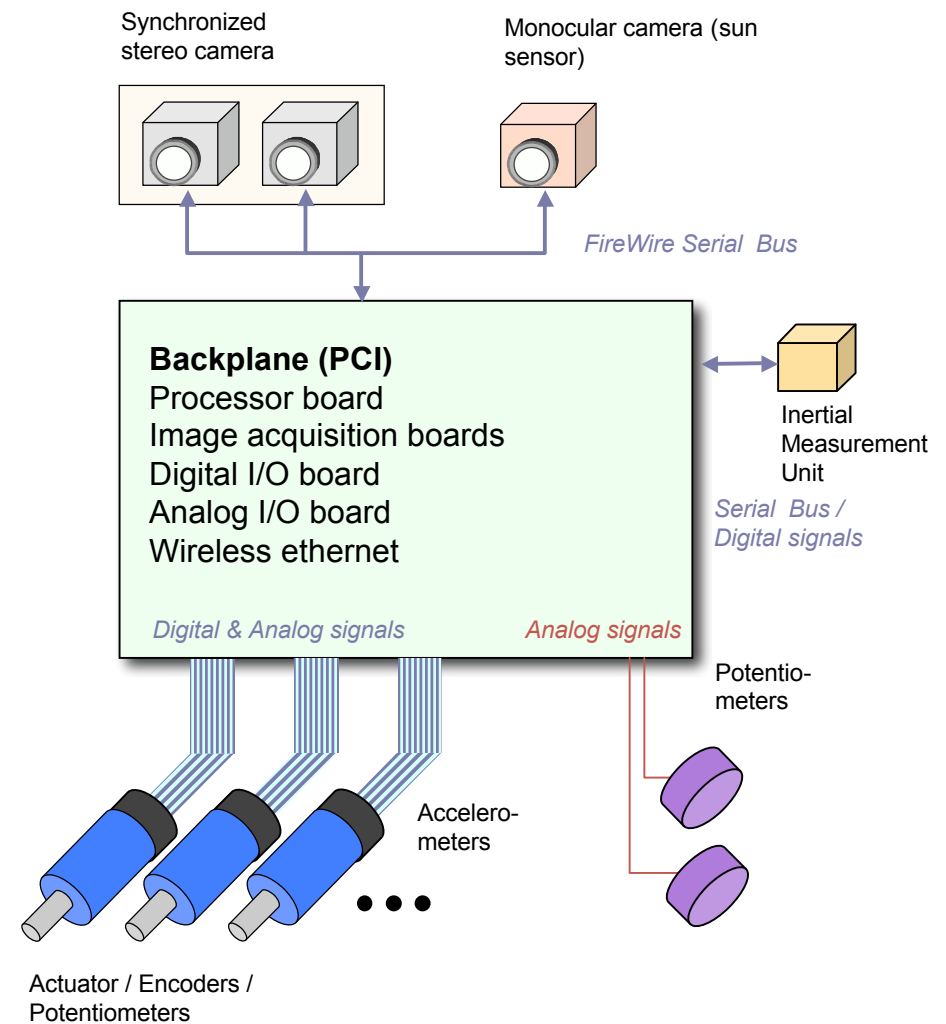
# Centralized Hardware Architecture



**FIDO**

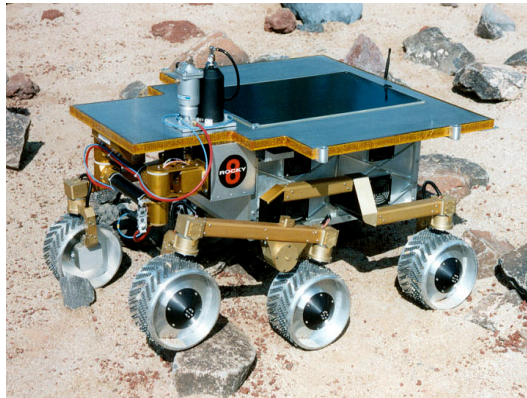
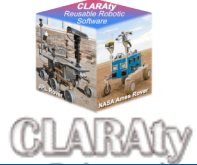


**Athena**





# Distributed Hardware Architecture



**Rocky 8**

## Rocky Widgets

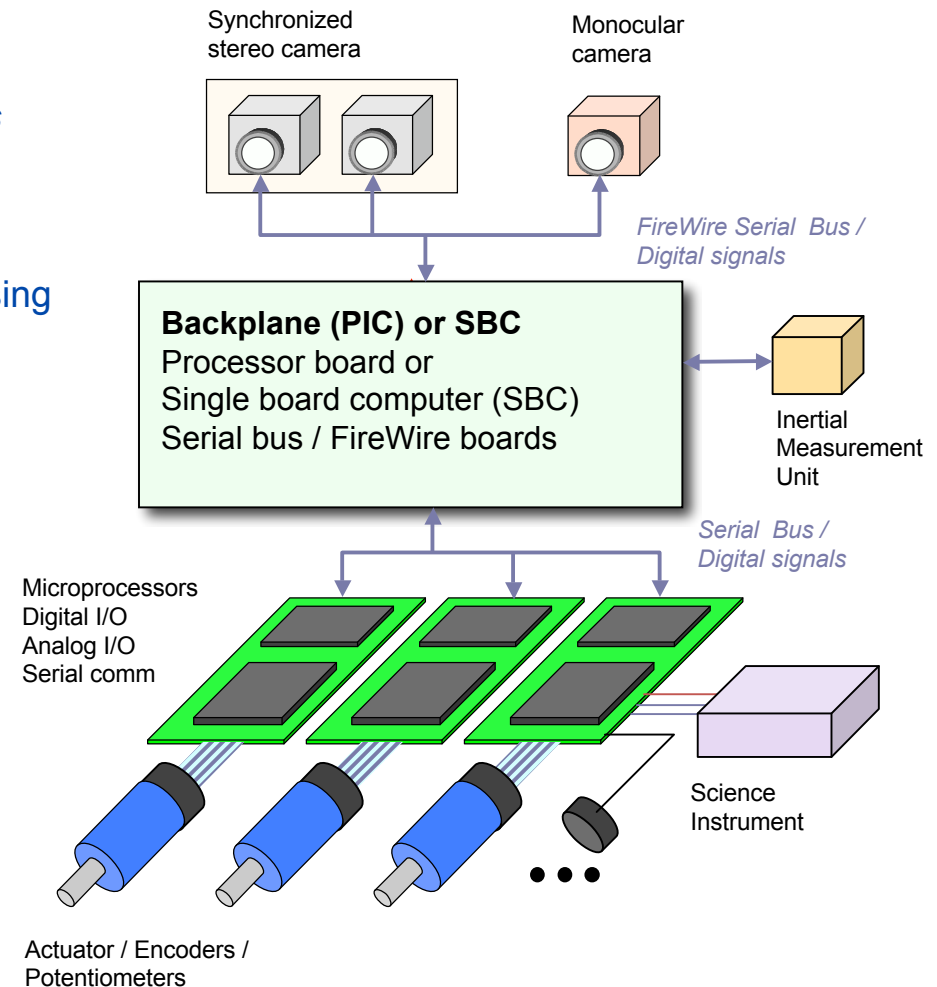
- I2C Bus
- Single Axis Controllers
- Current Sensing
- Digital I/O
- Analog I/O



**K9**

## K9 Controllers

- Serial Bus RS485
- PIC Servos
- Current Sensing
- Digital & Analog I/O



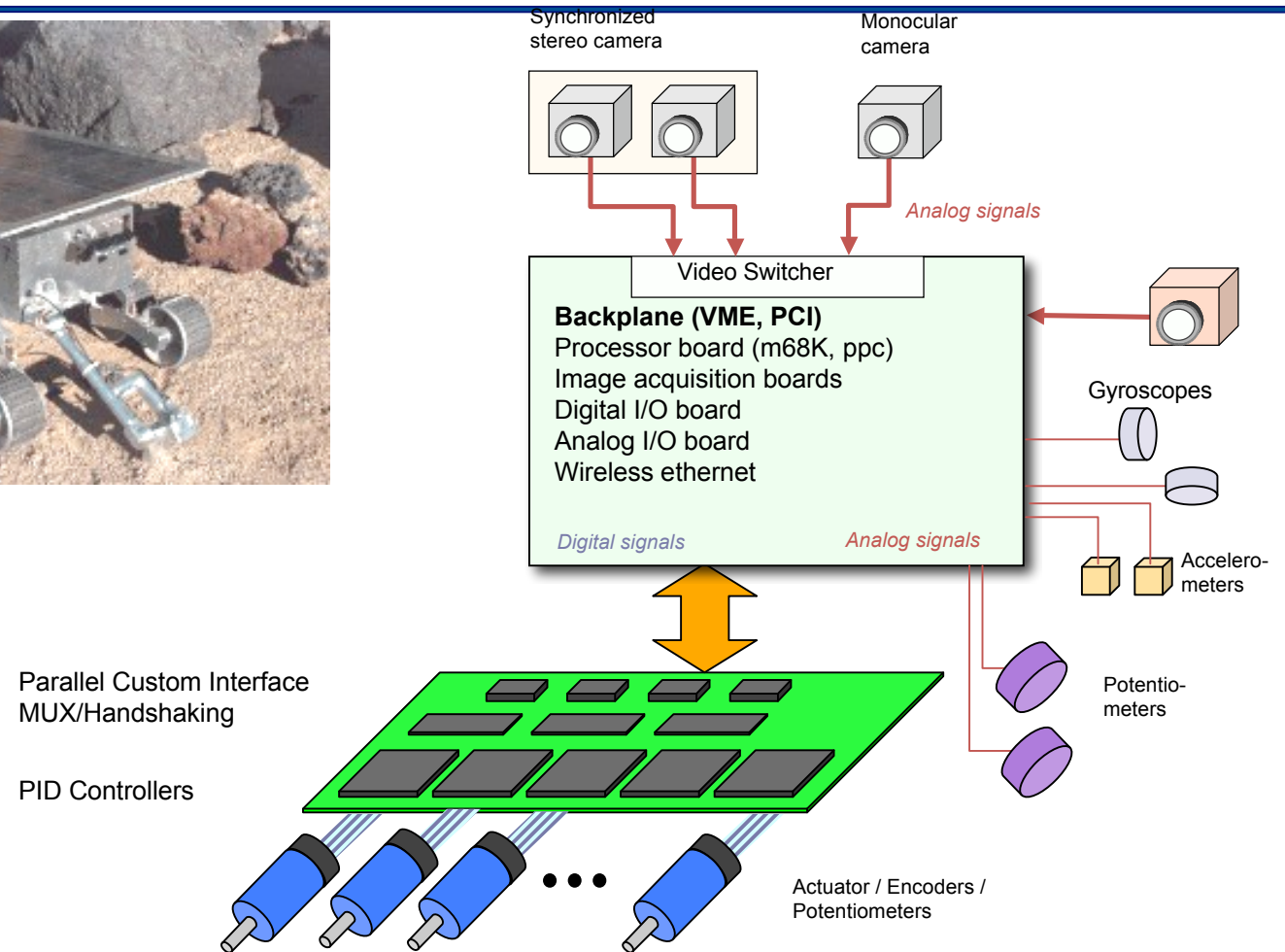


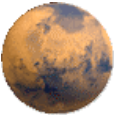


# Hybrid Architecture



*Rocky 7*



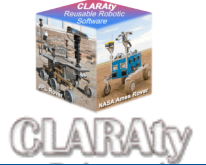


## ***Challenges of Interoperability***

- Mechanisms and Sensors
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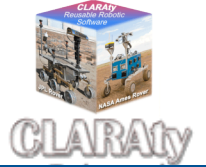
# Software Challenges for Algorithm Infusion



The *new* algorithms to be integrated may:

- Have architectural mismatches with the framework
- Include multiple orthogonal functionalities
- Make implicit assumptions about the platform
- Duplicate functionality in the framework
- Use incompatible data structures
- Be complex and hard to tune
- Depend on specific platform
- Require highly specialized domain expertise
- Be poorly implemented





# *Technical Approach*



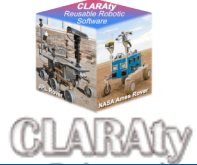
# Historical Antecedents



- **Late 80's - Early 90's:** parallel robotic developments
  - RSI, MOTES, Satellite Servicing, Robby, Mircoover
  - Very limited sharing of hardware or software
- **Mid 90's:** Mars rover research centralized with Rocky 7
  - First flight rover
- **Late 90's:** Expansion and diversification of rover work
  - Very limited software interoperability (Rocky 7, FIDO, Athena, DARPA)
  - Autonomy demonstration of Remote Agent Experiment (ARC and JPL)
  - MDS investigates reusable software for spacecraft control.
- **'99-Early 00:** Mars Technology Program envisions a unified autonomy architecture
  - Funds effort to unify autonomy and robotic control
  - Starts the CLARAty task in December 1999
- **Early 00's:** Development and deployment of common robotic software
  - Started development of a shared robotic software infrastructure among JPL, NASA ARC and Carnegie Mellon
  - CLARAty supports MTP's competed research program (01-03)
  - CLARAty supports Mars Science Laboratory Focused Technology validation program
- **Mid 00's:**
  - CLARAty supports MTP's NRA program (03-06) and other NASA programs
  - CLARAty completes its first public release



# State-of-the-Art in the Robotics Community

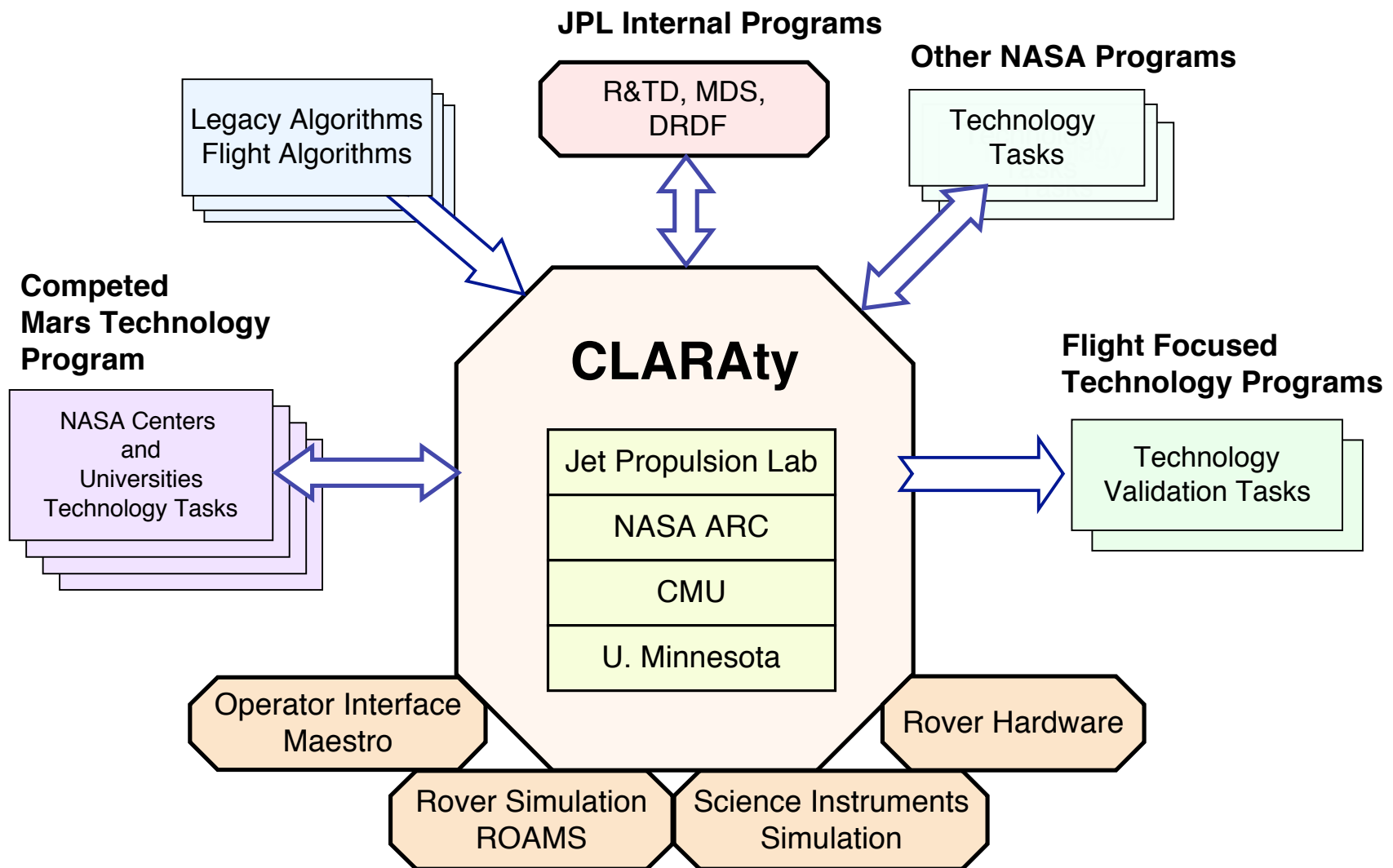


- **Within NASA:**
  - NASREM - temporal based decomposition. Evolved into 4D-RCS currently developed at NIST
  - ESMD funded a multi-center effort (JTARS) which followed the DoD JAUS model
- **Outside NASA**
  - **JAUS**
    - DoD/DARPA integration environment; Scope - all unmanned military vehicle; high level message-set based
  - **RosTa**
    - Funded by the EU and led by Fraunhofer in Germany; started in 2007
  - **Player/Stage**
    - Developed at USC; client server architecture; supports multiple COTS rovers; most recognized
  - **MS Robotics Studio**
    - Released in 2007; service oriented architecture; XML based message passing; supports heterogeneous programming languages
  - **OROCOS**
    - Funded by in part by the EU and led by K.U. Leuven; started in September 2001; provides CORBA based real-time tool kit, bayesian filtering library and kinematics and dynamics
    - Similar to CLARAty's libraries and abstractions
  - **LAAS**
    - Led by LAAS center in France; provides a similar decomposition of Functional Level / Decision Level
    - Support DL work; FL uses a framework similar to ControlShell's component architecture
  - **Miro**
    - Developed at a university in Germany for the Robocup competition; corba-based real-time framework
  - **Others**
    - Constellation from RTI (former ControlShell), NDDS from RTI, ESRP from Evolution, ROCI from U. Penn (ROCI), OSCAR from U. Texas, MARIE from U. Sherbrooke, ARIA from MobileRobots, Mobility from Irobot
- **Comparison:**
  - Several hierarchical decomposed system; disagreement on how to decompose the hierarchy
  - Limited functionality and flexibility to support development of advanced algorithms
  - Most are constrained for supporting custom robots



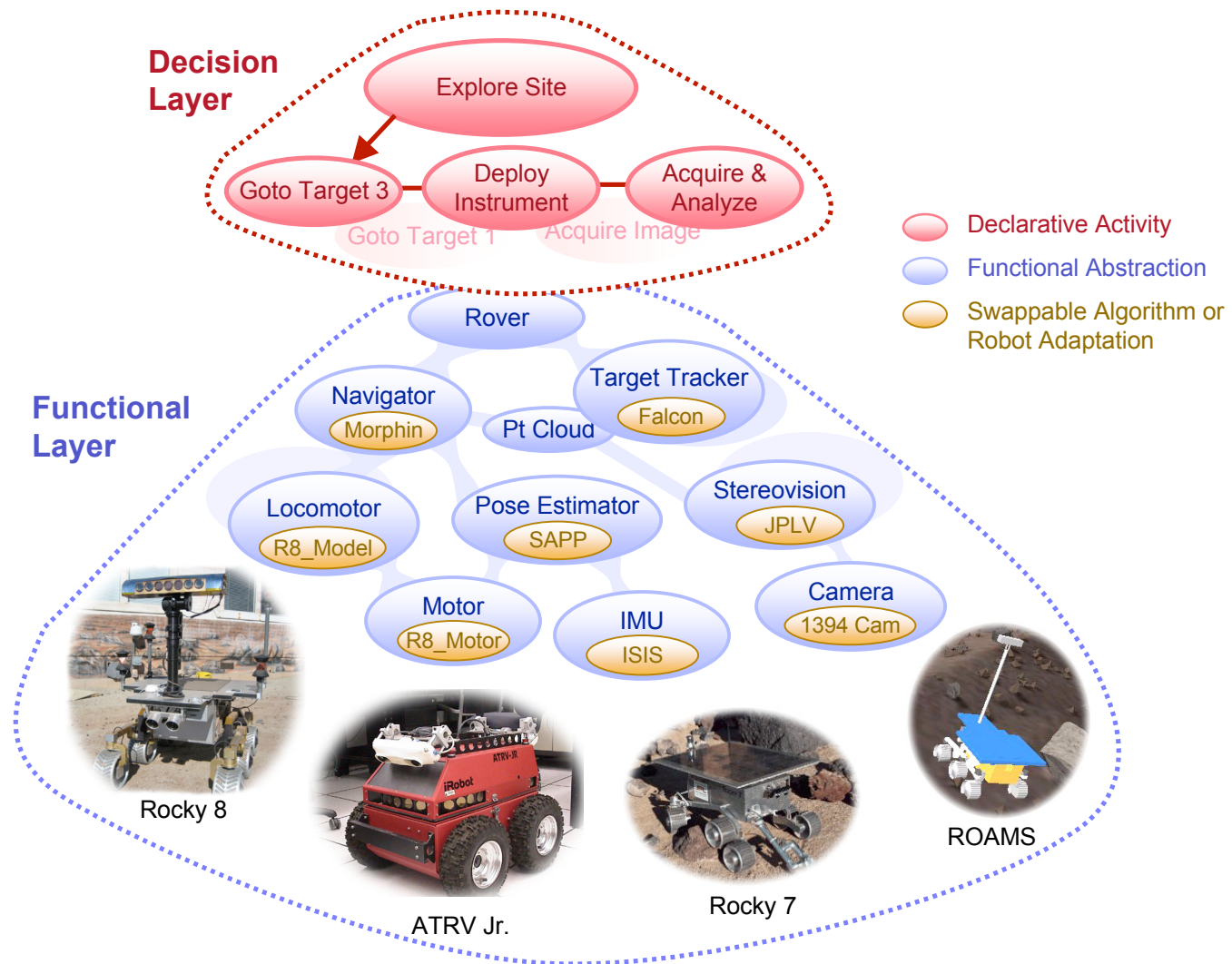


# Process and Collaborations





# Overall Architecture

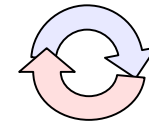




# Technical Approach



- Capture **requirements** from domain experts
- Use **global perspective** across domains (motion, vision, estimation, navigation)
- Identify **recurring patterns** and **common infrastructure** therein
- Use **domain expert** to guide design
- Define **proper interfaces** for each subsystem
- Develop **generic framework** to support various implementations
- Adapt **legacy implementations** to validate framework
- **Encapsulate** when re-factoring is not feasible or affordable
- Develop **regression tests** where feasible
- **Test** on multiple robotic platforms and **study limitations**
- **Feed** learned experience **back** into the design
- **Review** and **update** to address limitations

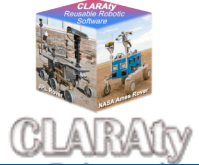


*After several iterations one hopes to have achieved a truly reusable infrastructure*





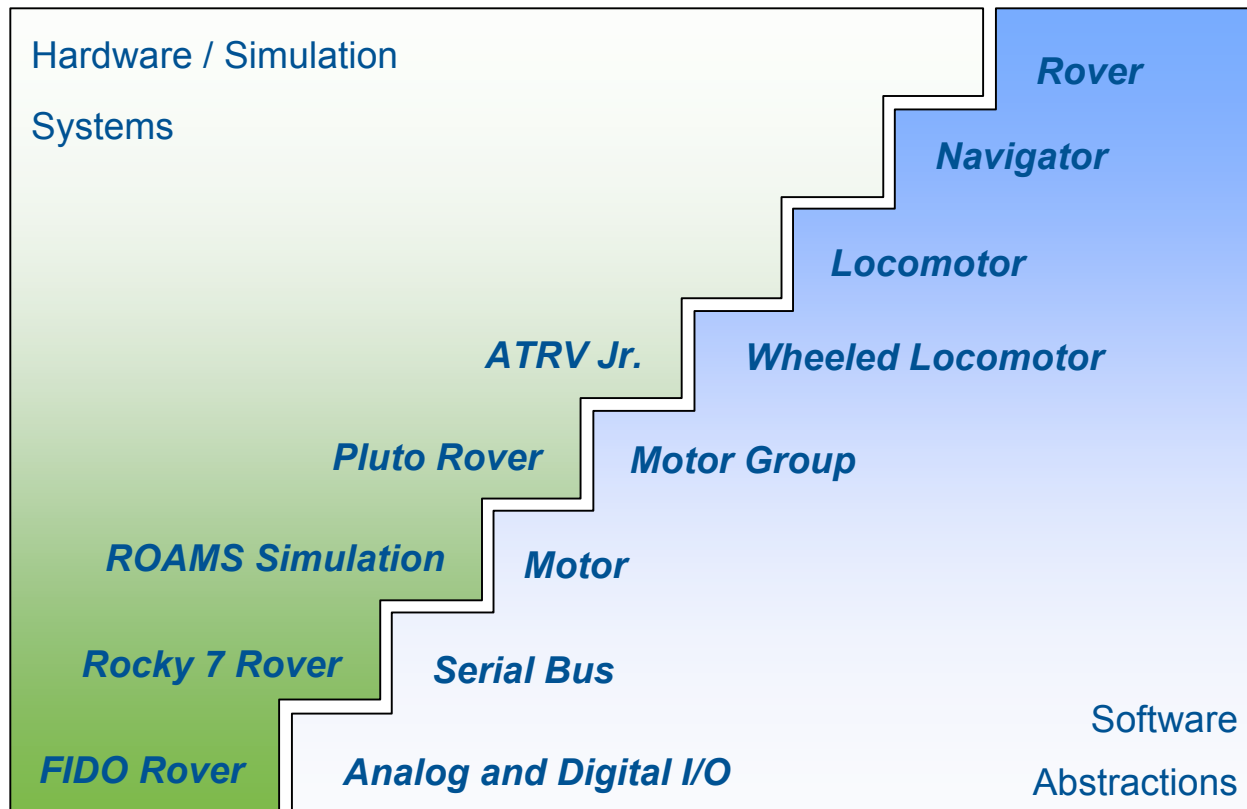
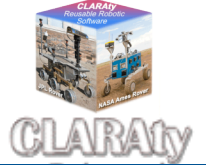
# Declarative vs. Procedural Programming



Declarative Programming	Procedural Programming
<pre>Rover.navigate_from_to(Loc1, Loc2)</pre> <p><b>Preconditions:</b></p> <pre>near(Loc1, Loc2) rover.has_power(Loc1, Loc2) rover.has_time(Loc1, Loc2)</pre> <p><b>Effects:</b></p> <pre>rover.is_at(Loc2)</pre>	<pre><b>If</b>    near(Loc1, Loc2) AND        rover.has_power(Loc1, Loc2) AND        rover.has_time(Loc1, Loc2) AND <b>Then:</b> rover.navigate_from_to(Loc1, Loc2)</pre>



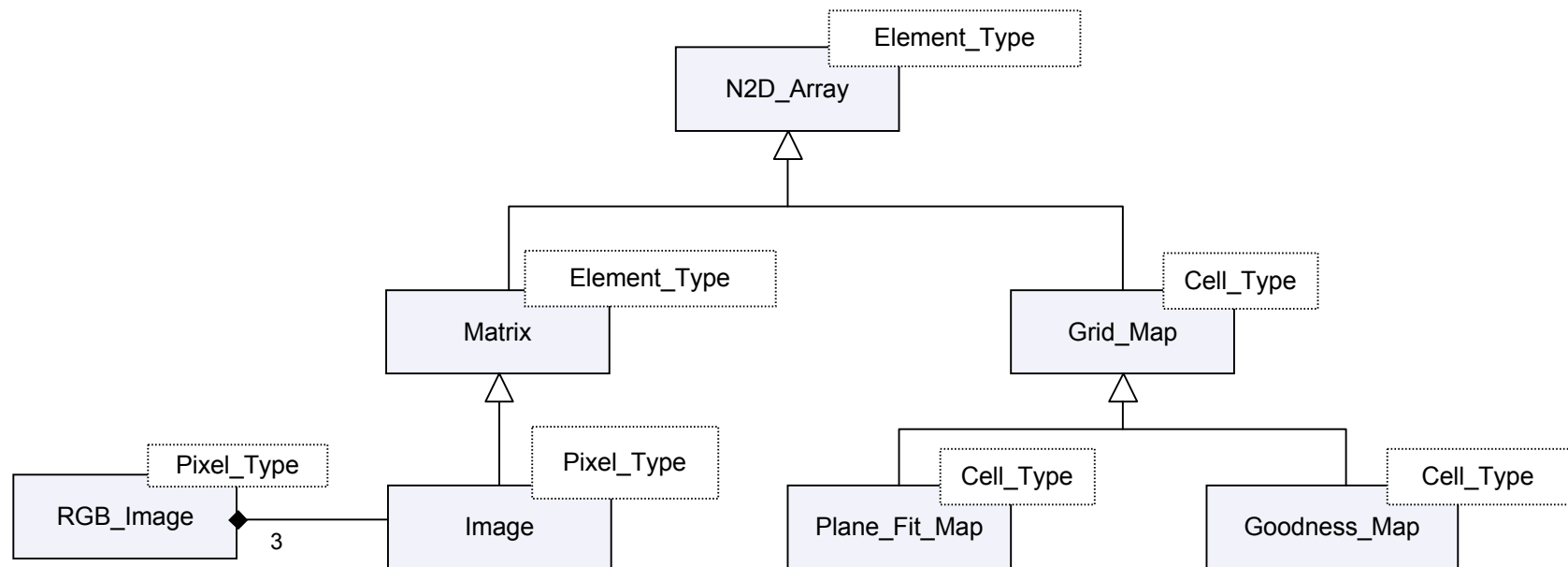
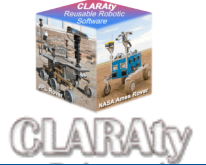
# Guideline I: Multi-level Access



Multi-level mobility abstractions



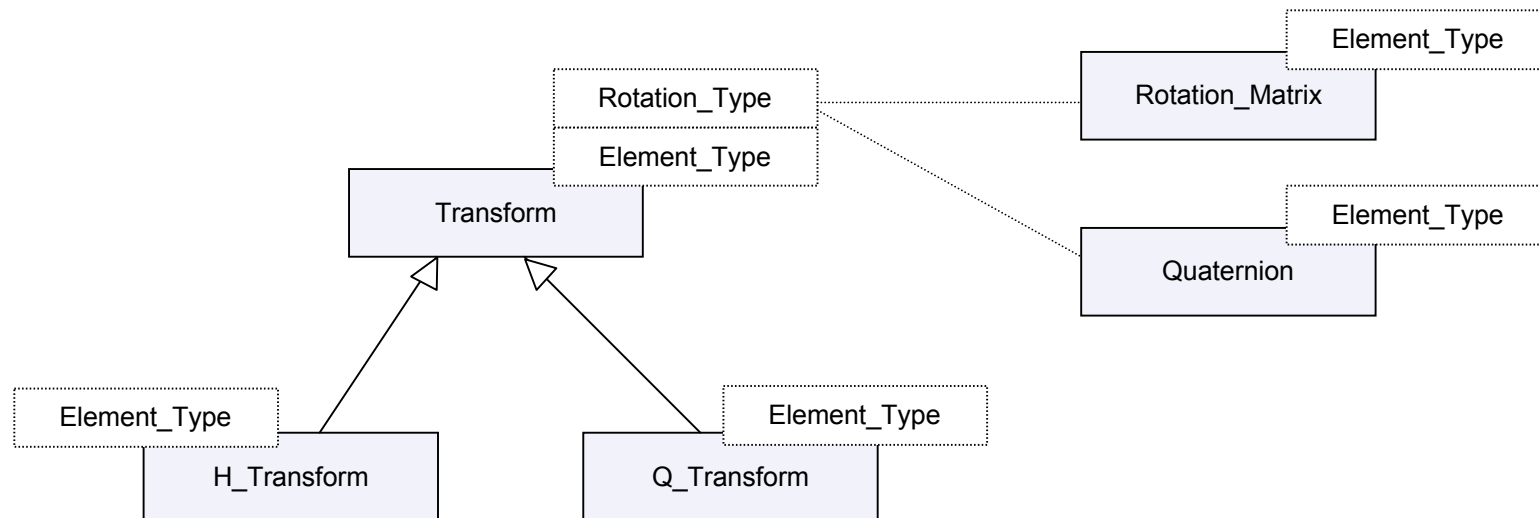
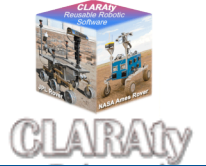
# Guideline II: Common Data Structures





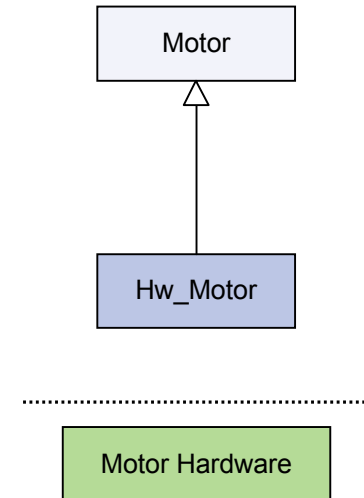
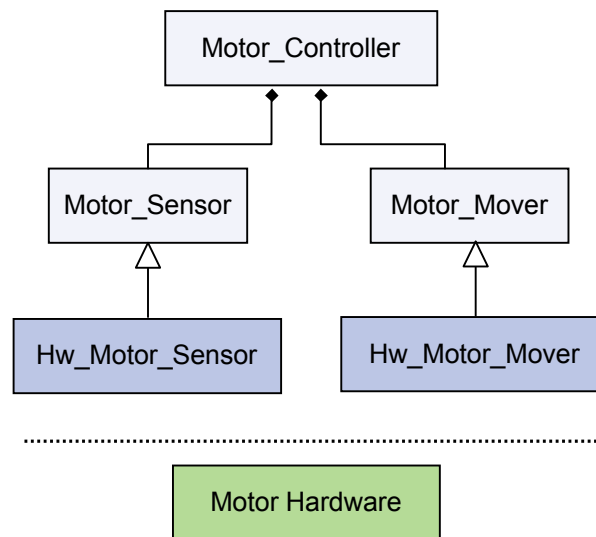
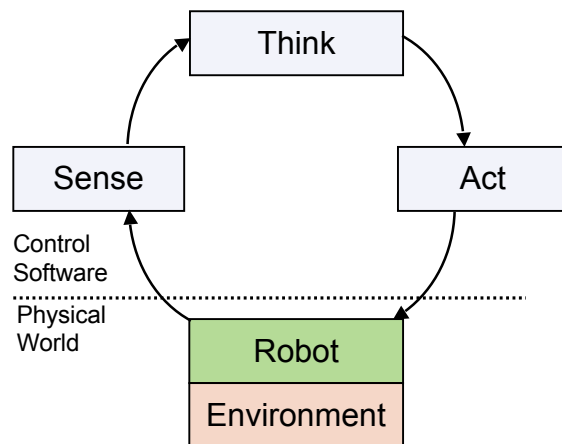


## Guideline III: Interoperable Transformations



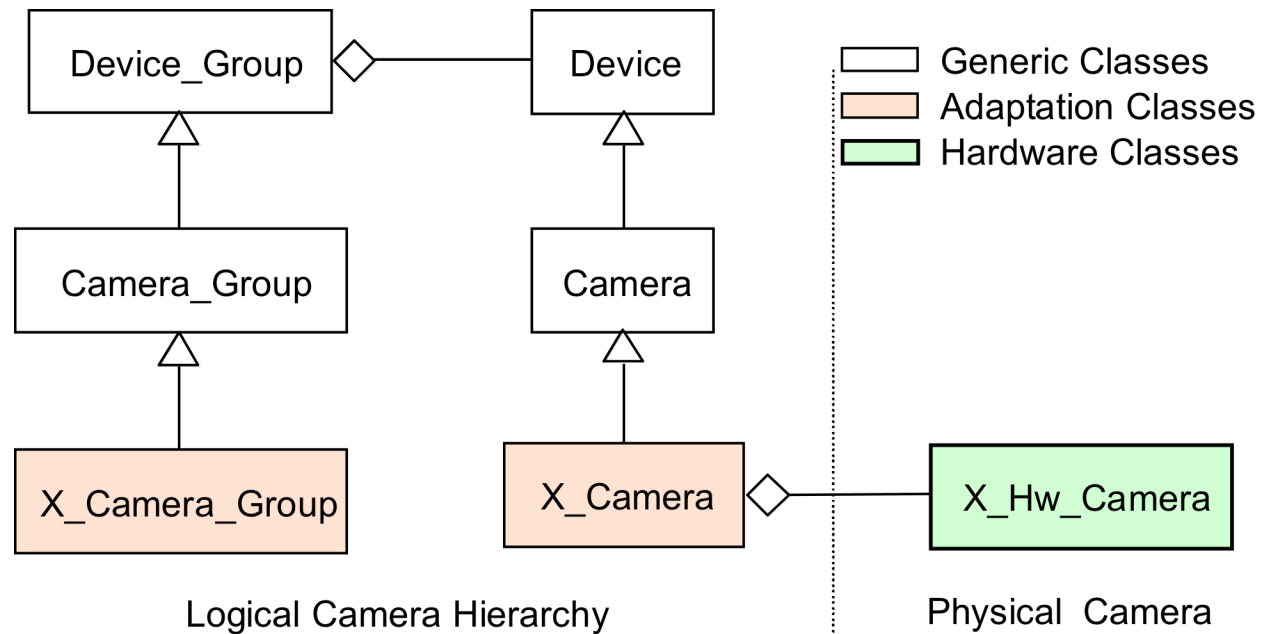


# Guideline IV: Abstract Model



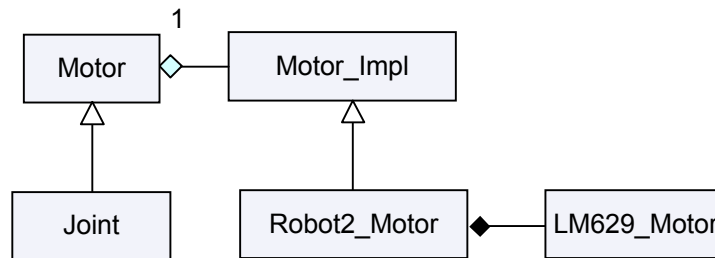


## Guideline V: Separating Logical from Physical Hierarchies

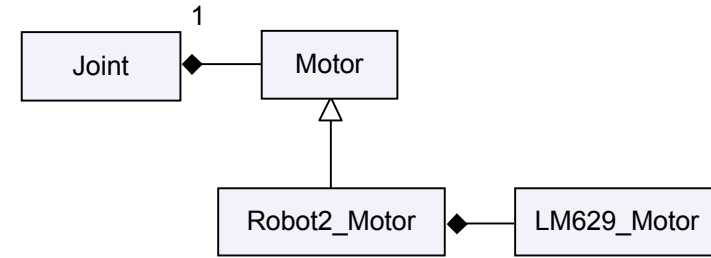




# Guideline V: Separating Logical from Physical Hierarchies

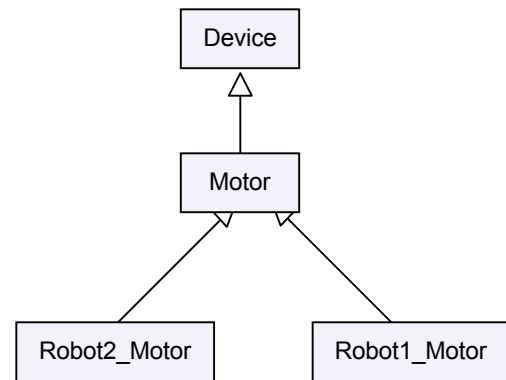


(a) Joint is a Motor



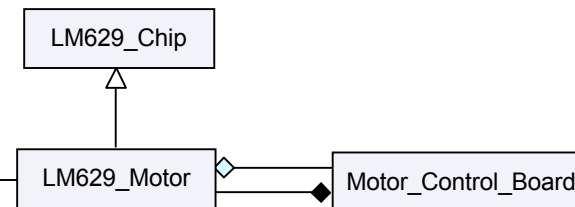
(b) Joint has a Motor

Revision 2



Logical Motor Architecture

Revision 3

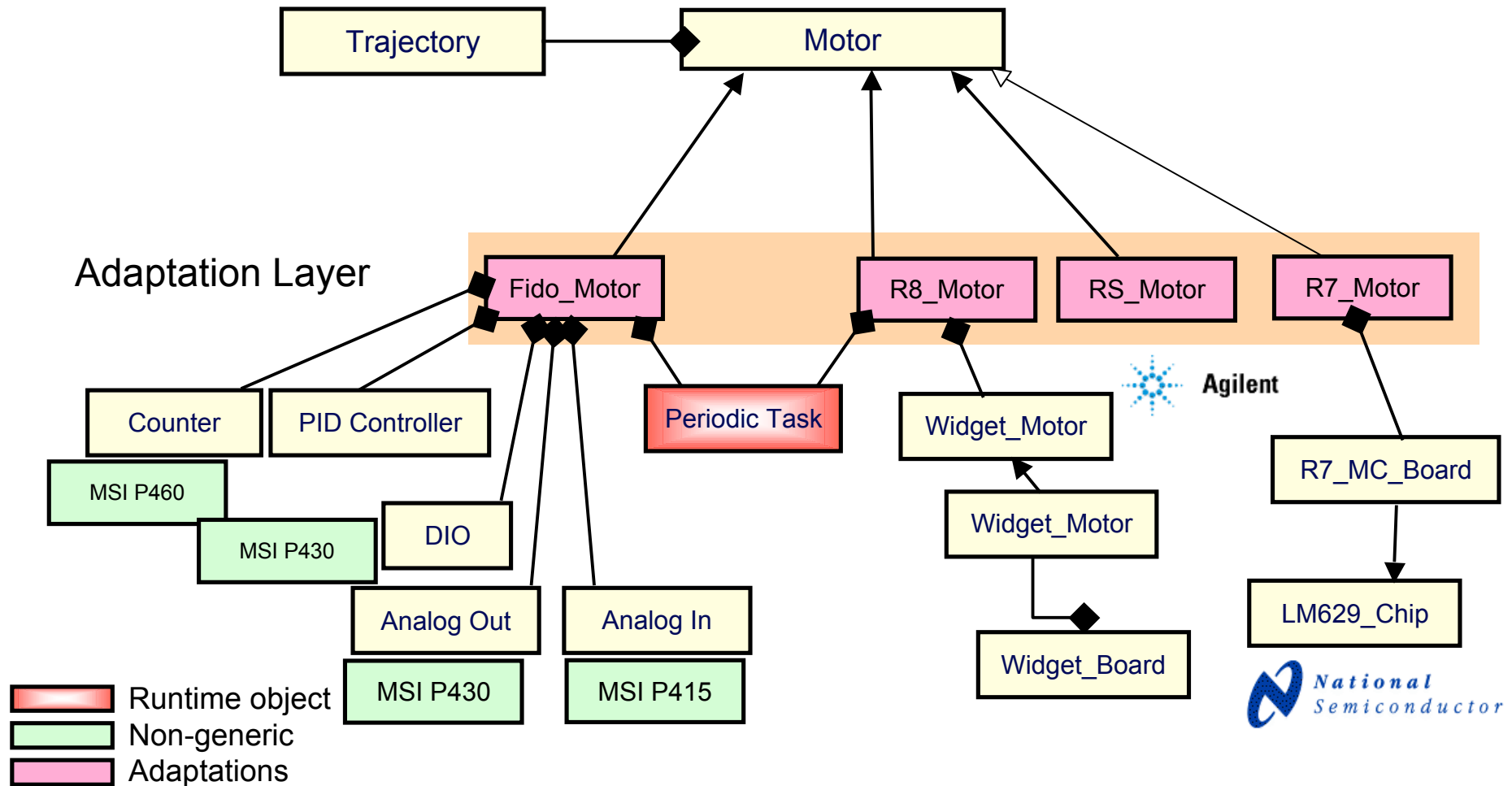


Physical Motor Architecture





## Guideline IX: Encapsulate Run-time Model

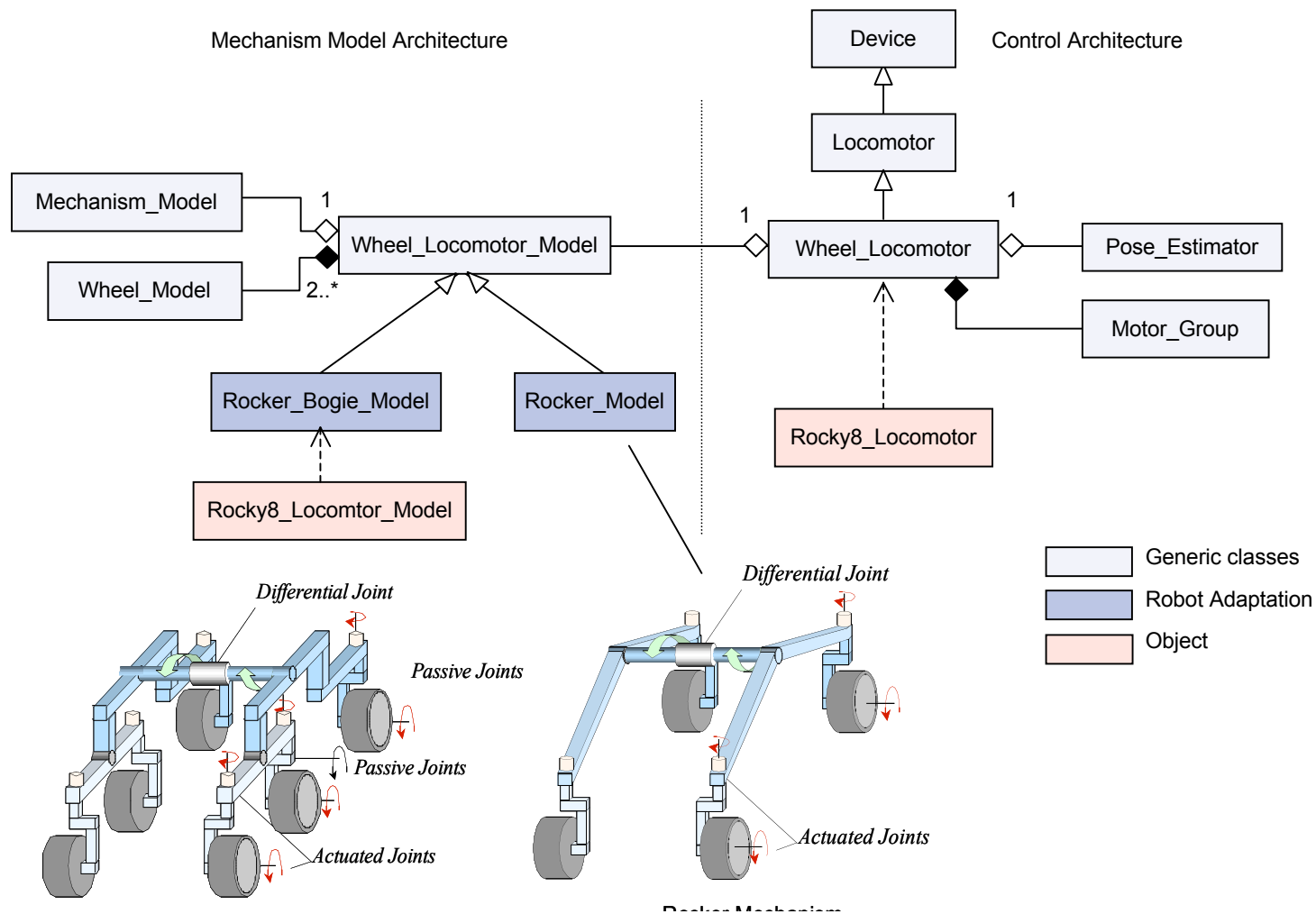




# Guideline VI: Separating Models from Control

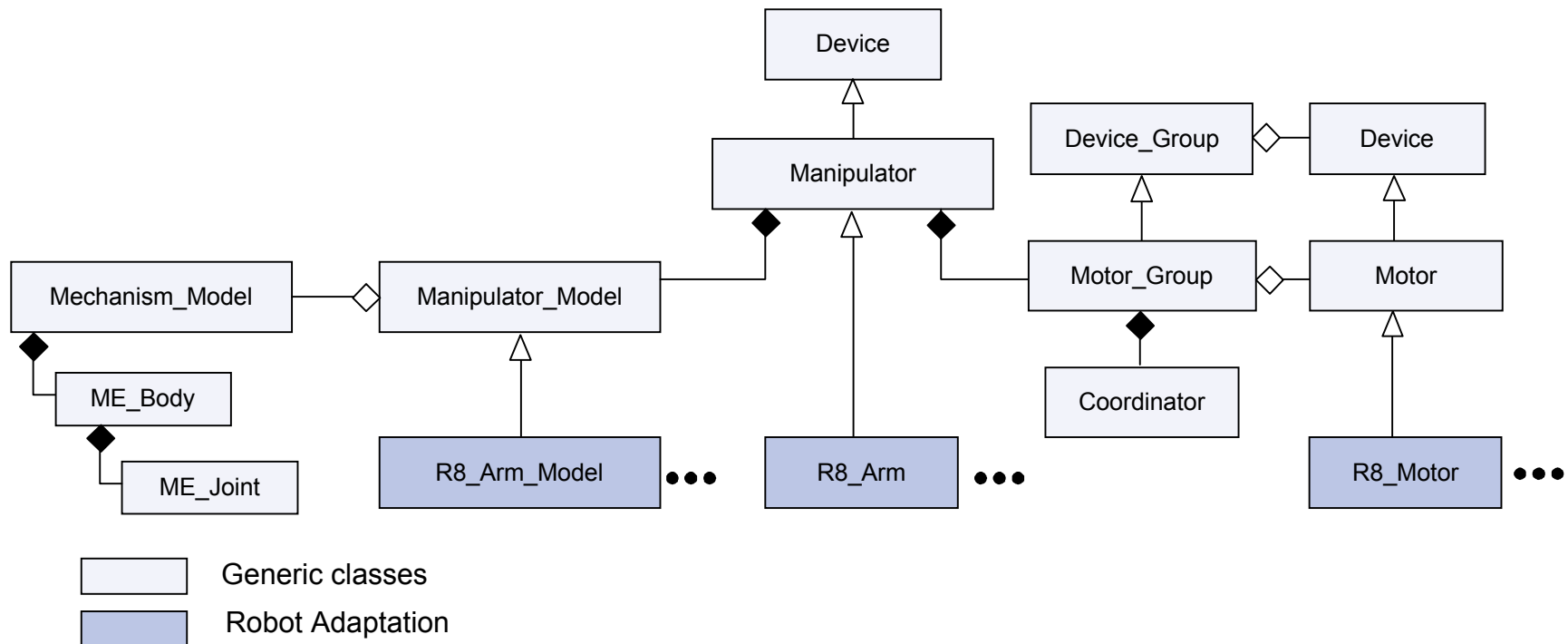


## Separating model and control





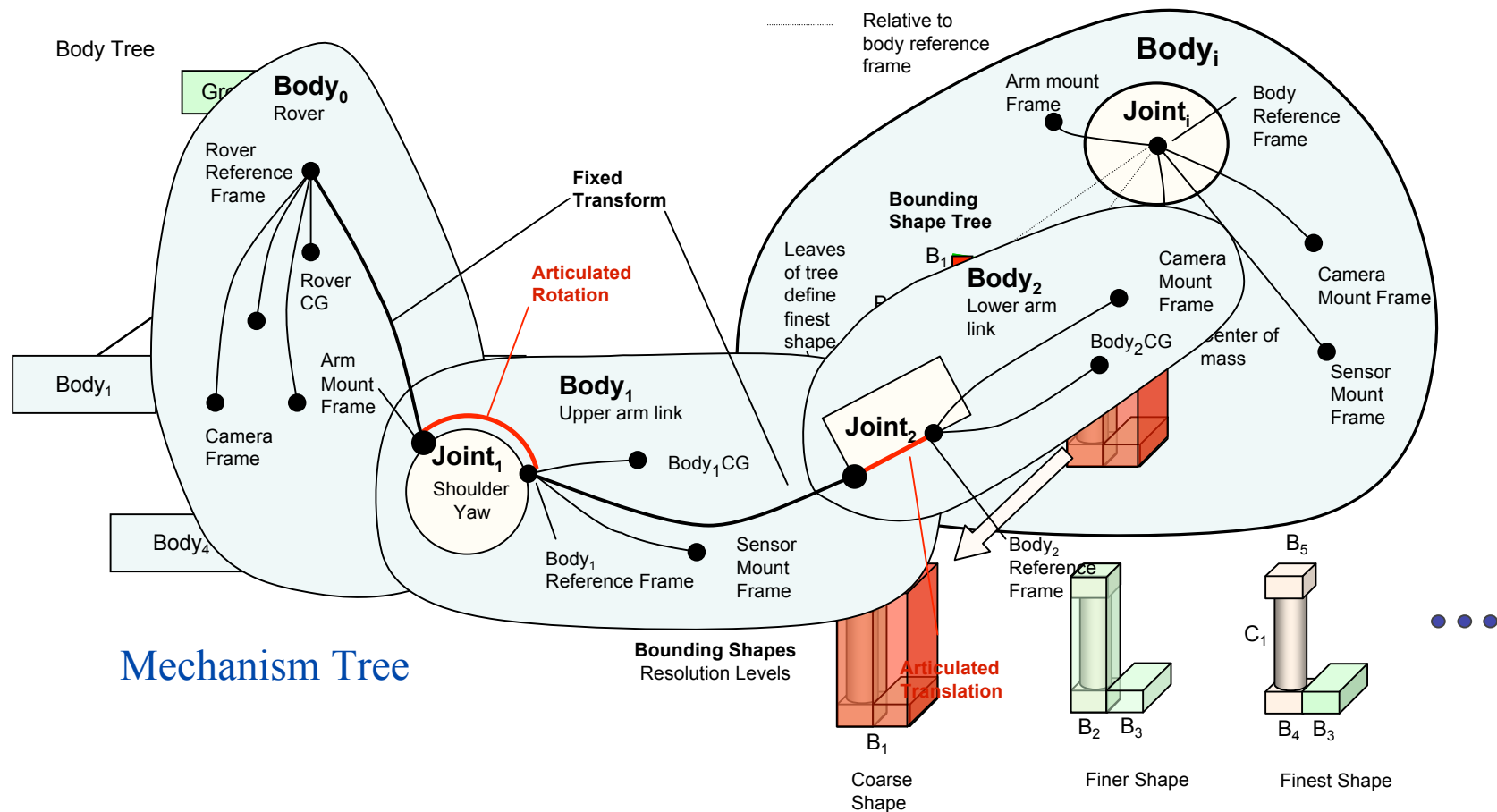
# Guideline VI: Separating Models from Control





## Unifying mechanism model

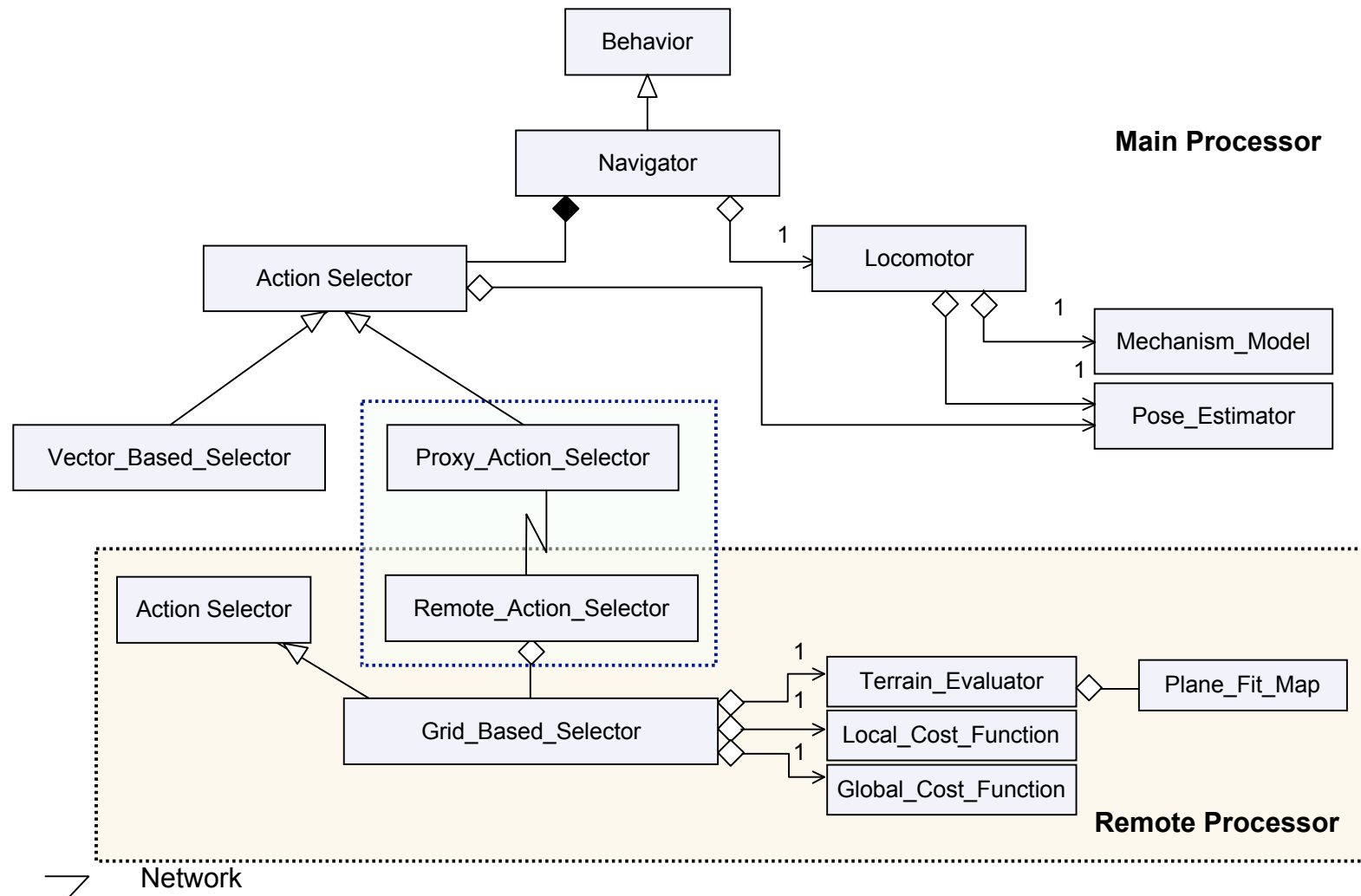
## Bodies and Joints







## Guideline VIII: Separating Interface from Implementation

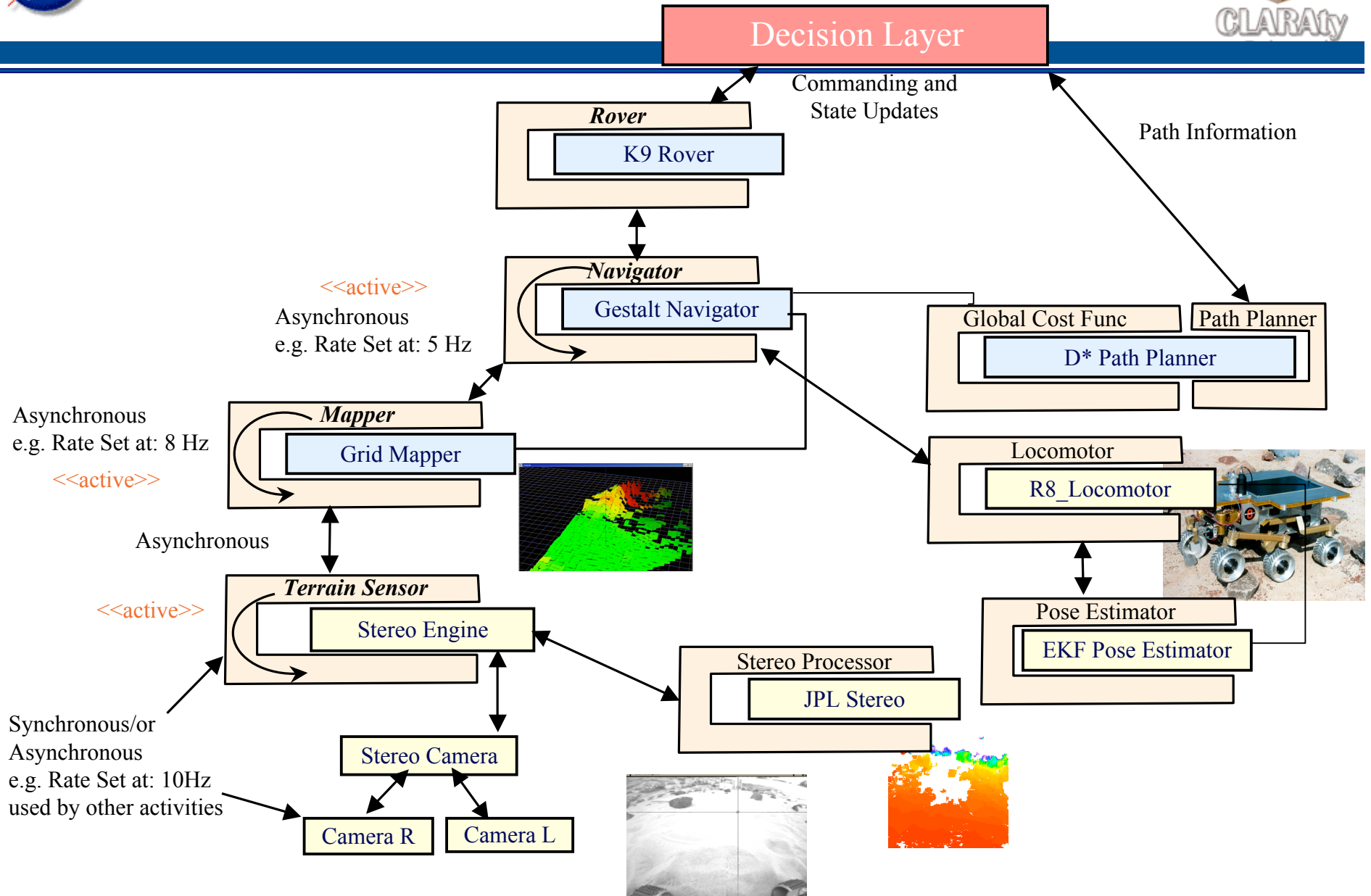




# Putting it All Together - Swapping Navigation Algorithms



CLARATy

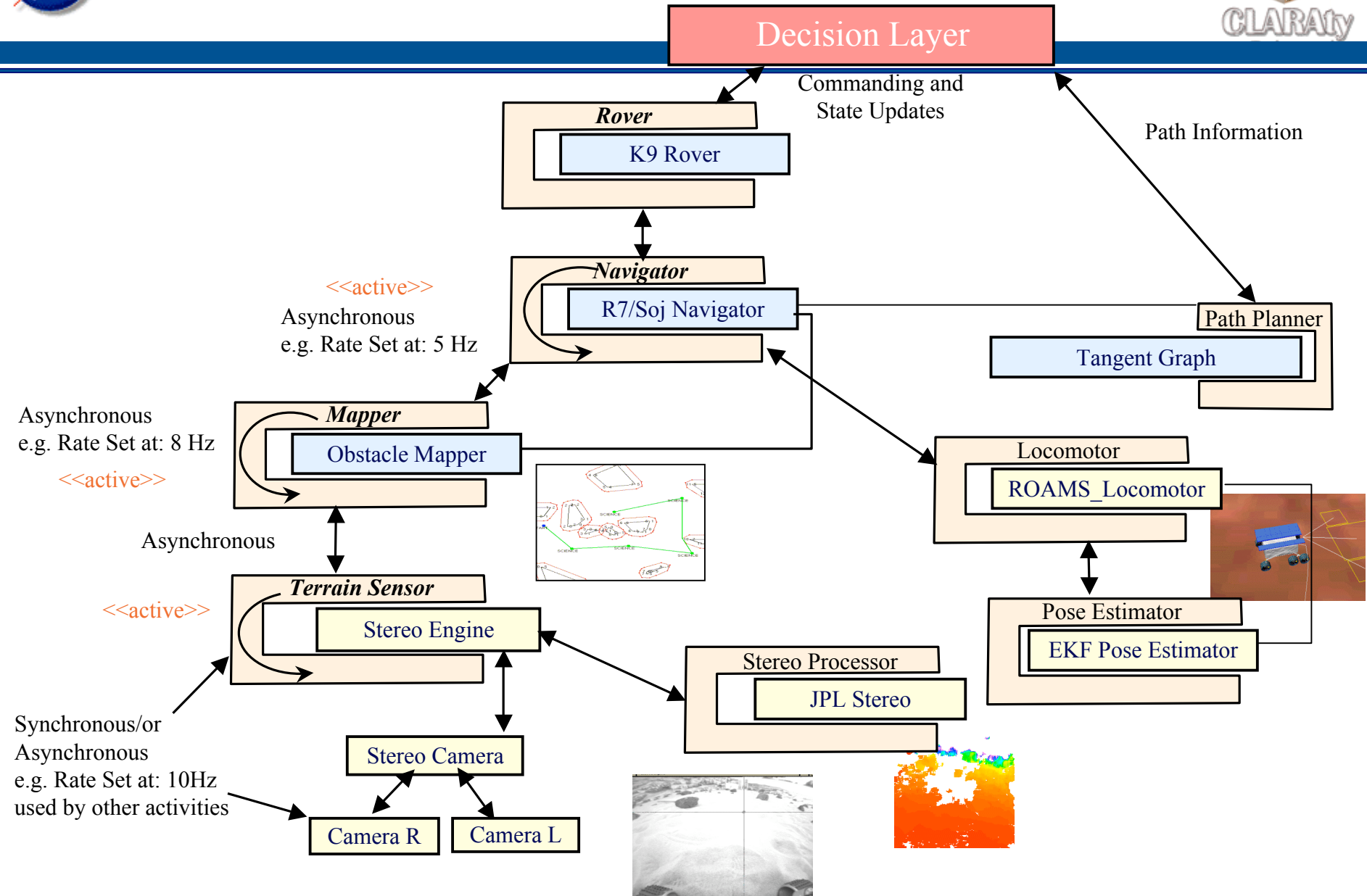


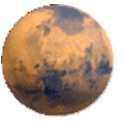


# Putting it All Together - Swapping Navigation Algorithms



CLARAty





## ***Status and Future Plans***





# Product: CLARAty Modules



- 425 modules in repository
- 54 modules are technology contributions (~13%)
- 870K lines of logical C++/C (300K from MER)
  - Major increase due to incorporation of MER FSW and navigation
- Six rover adaptations
  - K10, Rocky 8, FIDO, K9, Rocky 7, ATRV, Athena, and DistAv Pluto
- 44 modules released in the public repository
- 4 are ITAR restricted
- 25 may be IP restricted
- remaining modules are ITAR clear and planned for public release

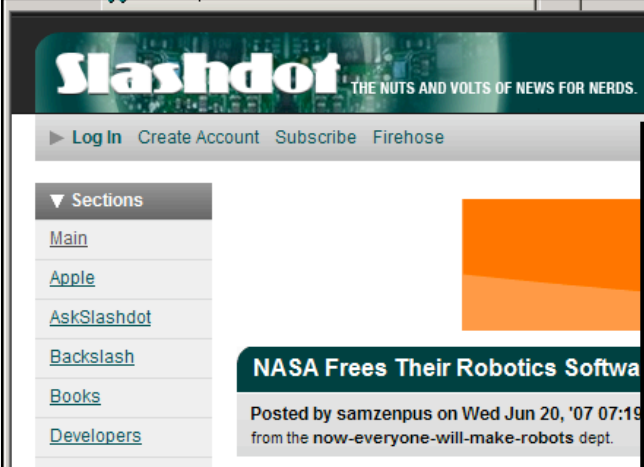
#### CLARAty Integration Levels

- Level I – Deposited
- Level II – Encapsulated
- Level III – Refactored
- Level IV – Formally reviewed
- Level V – Publicly released



# Sample Coverage of CLARAty Release





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**NASA Frees Their Robotics Software**

Posted by samzenpus on Wed Jun 20, '07 07:19 from the now-everyone-will-make-robots dept.



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**NASA выпустили CLARAty под лицензией JPL**

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**NASA выпустили CLARAty под лицензией JPL**

CLARAty это уровень архитектуры определяющий автономность роботов. Первый релиз v.0.10-beta, доступен на <http://claraty.jpl.nasa.gov>.

Данный выпуск включает в себя определение правил взаимодействия, и интеграции различных функций, таких как дальность, навигация, передвижение, планирование.

Комплекс CLARAty был спонсирован Mars Technology Program для обеспечения интеграции между различными программами роботов для исследования марса.

Для скачивания доступно 44 модуля под лицензией JPL и содержит порядка 10% от общего количества CLARAty модулей и 30% модулей запланированных для будущих выпусков.

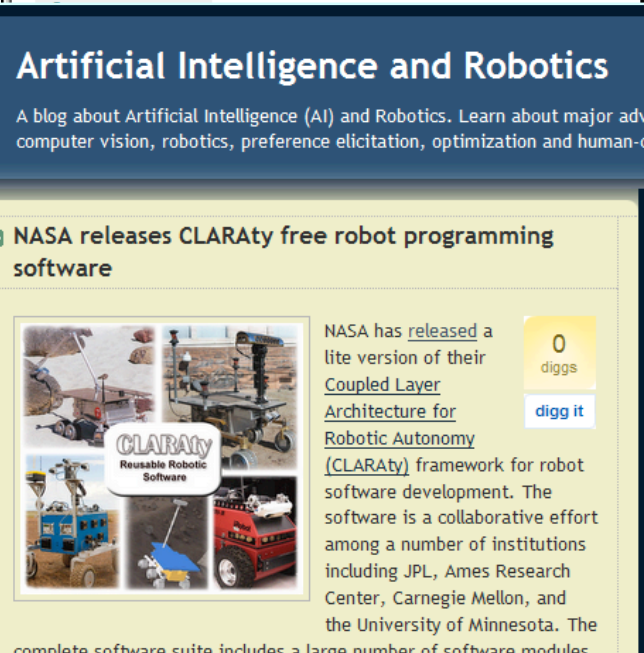
Модули предназначены для обседа математической базы, передвижения, координации, трансформации, и управления подвижными частями машин, включая, колесные, шагающие, и гибридные устройства. Также, модули включают поддержку цифрового и аналогового ввода/вывода, камеры, в том числе цветные, и представление поверхности в видео режиме.

>>> First Public Release of CLARAty Software.

anonymous (\*) (21.06.2007 6:01:51)  
Проверено: cavia\_porcellus (\*) 21.06.2007 11:36:03

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**NASA releases CLARAty free robot programming software**

NASA has released a lite version of their Coupled Layer Architecture for Robotic Autonomy (CLARAty) framework for robot software development. The software is a collaborative effort among a number of institutions including JPL, Ames Research Center, Carnegie Mellon, and the University of Minnesota. The complete software suite includes a large number of software modules

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**CLARAty 0.10 Beta - FREE DOWNLOAD**

DOWNLOAD LOCATIONS FOR CLARAty

**RATATOUILLE**

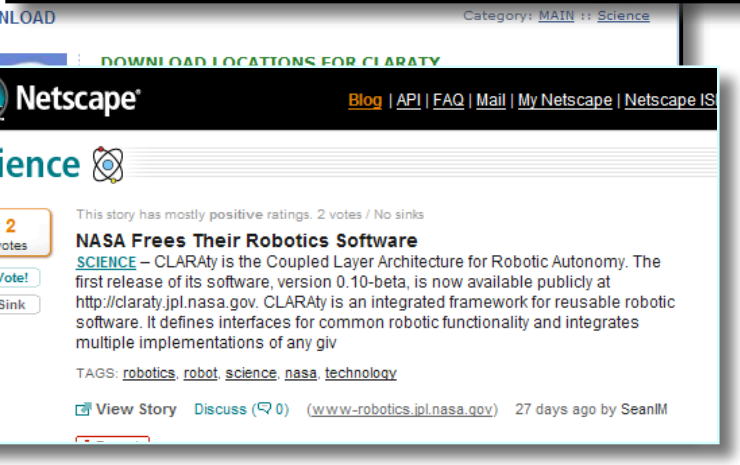
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**NASA Frees Their Robotics Software**

**SCIENCE** – CLARAty is the Coupled Layer Architecture for Robotic Autonomy. The first release of its software, version 0.10-beta, is now available publicly at <http://claraty.jpl.nasa.gov>. CLARAty is an integrated framework for reusable robotic software. It defines interfaces for common robotic functionality and integrates multiple implementations of any given function.

TAGS: [robotics](#) [robot](#) [science](#) [nasa](#) [technology](#)

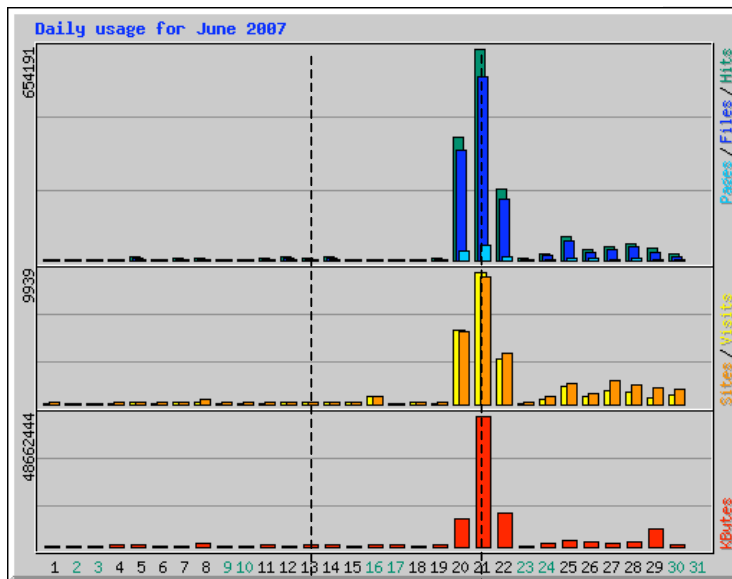
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# CLARAty Release Statistics

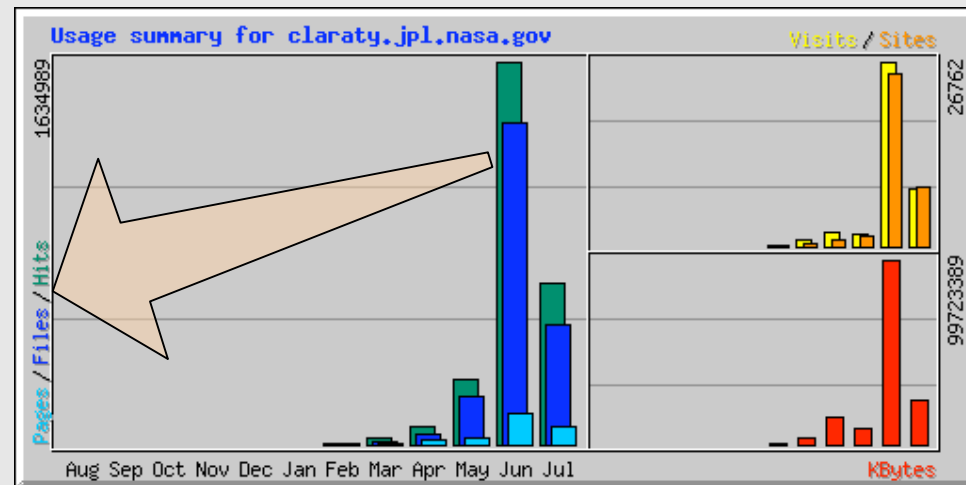


CLARAty



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Summary by Month

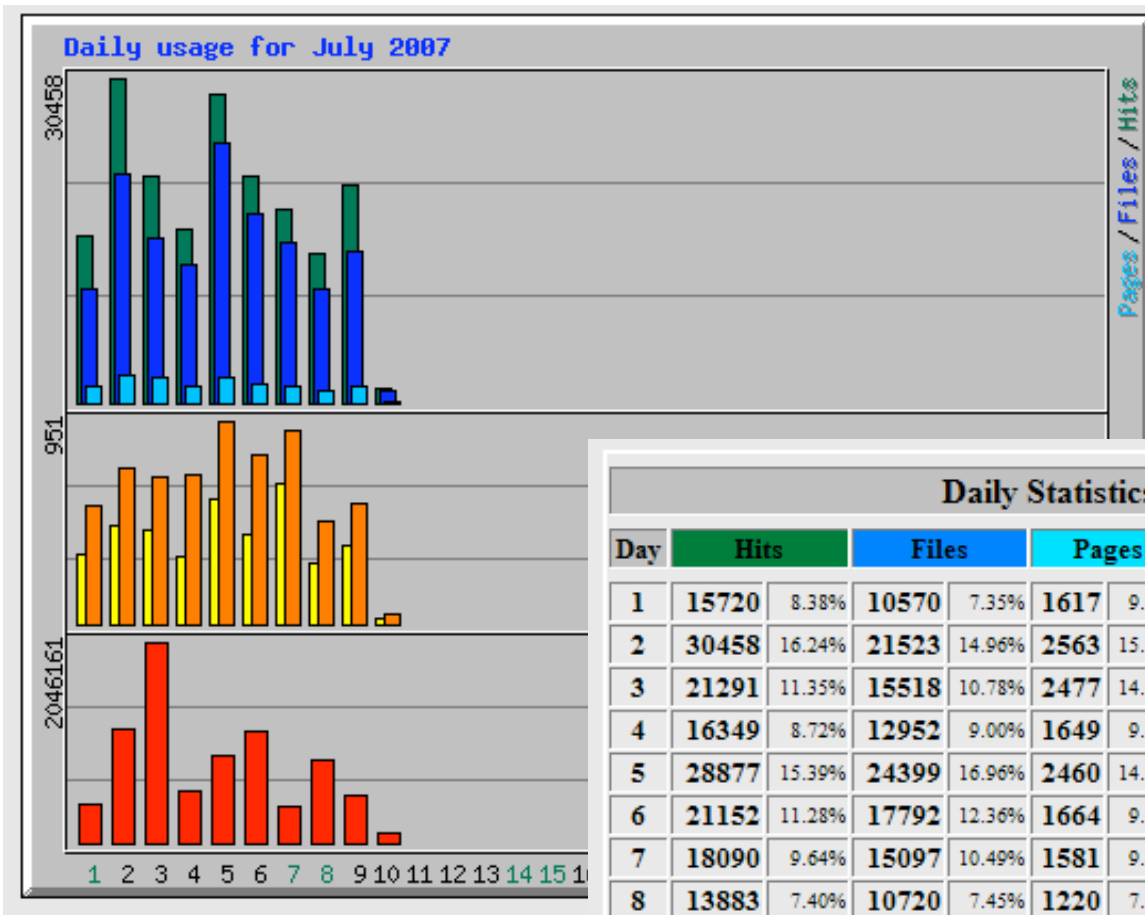
Month	Daily Avg				Monthly Totals					
	Hits	Files	Pages	Visits	Sites	KBytes	Visits	Pages	Files	Hits
<a href="#">Jul 2007</a>	18757	14389	1680	388	4765	7940189	3885	16803	143891	187574
<a href="#">Jun 2007</a>	54499	45656	4451	892	25123	99723389	26762	133547	1369697	1634989
				793	58	1403	8890087	1821	24586	202490
				555	67	936	14531668	2022	16650	47578
				297	59	457	3127604	837	4169	15540
				132	36	113	238984	108	398	2818
							134451921	35435	196153	1782010
										2210002

## Stats

- Strong interest among general public and robotics community.
- Tens of web sites carried articles on the release
- Articles written in multiple languages and hosted world wide
- CLARAty site received around **2.5 million** hits in two months
- Total of **3,300 downloads** of the software in one month
- Hundreds of comments from the public



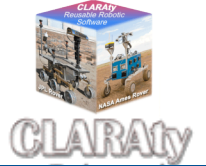
# CLARAty Web Site Statistics: Stable Increase in Traffic – July 2007



Daily Statistics for July 2007												
Day	Hits		Files		Pages		Visits		Sites		KBytes	
1	15720	8.38%	10570	7.35%	1617	9.62%	327	8.42%	549	11.52%	403881	5.09%
2	30458	16.24%	21523	14.96%	2563	15.25%	464	11.94%	730	15.32%	1147833	14.46%
3	21291	11.35%	15518	10.78%	2477	14.74%	441	11.35%	686	14.40%	2046161	25.77%
4	16349	8.72%	12952	9.00%	1649	9.81%	317	8.16%	698	14.65%	538035	6.78%
5	28877	15.39%	24399	16.96%	2460	14.64%	583	15.01%	951	19.96%	895687	11.28%
6	21152	11.28%	17792	12.36%	1664	9.90%	416	10.71%	789	16.56%	1131185	14.25%
7	18090	9.64%	15097	10.49%	1581	9.41%	661	17.01%	909	19.08%	362198	4.56%
8	13883	7.40%	10720	7.45%	1220	7.26%	284	7.31%	476	9.99%	837820	10.55%
9	20370	10.86%	14283	9.93%	1479	8.80%	372	9.58%	567	11.90%	487337	6.14%
10	1384	0.74%	1037	0.72%	93	0.55%	27	0.69%	50	1.05%	90052	1.13%



# Summary

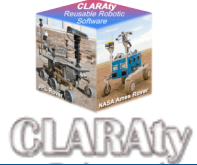


- Presented a quick overview of the CLARAty effort toward increasing the reuse of robotic software
- Deployed at multiple institutions
- Deployed on multiple heterogeneous robots
- Integrated multiple technologies from different institutions
- Delivered algorithms for formal validation
- Enabled new technology developments on multiple platforms
- Integrated flight algorithms for detailed performance characterization and operation on research rovers.
- Taking a technology from inception, to development in CLARAty, to validation, and now to integration into flight
- Completed the first public release and interest from the community looks promising





# Acknowledgement: CLARAty Developers (Core Team)



- NASA Ames Research Center
  - Lorenzo Flueckiger (*Co-I*)
  - Hans Utz
- Carnegie Mellon
  - Reid Simmons (*Co-I*)
  - Nick Melchior
  - David Apfelbaum
- University of Minnesota
  - Stergios Roumeliotis (*Co-I*)
  - Anastasios Mourikis
  - Nikolas Trawny
- Jet Propulsion Laboratory
  - Issa A.D. Nesnas (*PI*)
  - Tara Estlin (*PI - DL*)
  - Hari Das Nayar
  - Mihail Pivtoraiko
  - Richard Petras
  - Michael McHenry
  - Daniel Clouse
  - Dan Gaines
  - Robert Steele
  - Khaled Ali
  - Won Kim
  - Kelly Breed
  - Jeffrey Edlund
- Key Former Developers
  - Richard Volpe
  - Anne Wright
  - Max Bajracharya
  - Clay Kunz
  - Antonio Diaz Calderon
  - Chris Urmson
  - Richard Madison
  - I-Hsiang Shu
  - Randy Sargent


For the complete list of key former developers and contributors see:  
<http://claraty.jpl.nasa.gov> -> Project -> Team



# Team Received One NASA Center Best Award in 2006



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**CLARAty**  
Reusable Robotic Software



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SOFTWARE

PROJECT

TEST BED

HARDWARE

OBJECTIVES

PUBLICATIONS

PRESENTATIONS

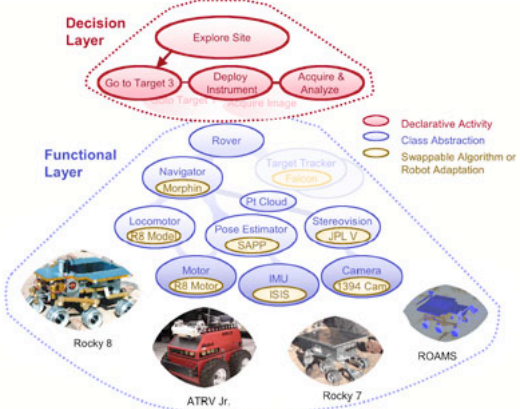
MOVIES

ACCESS

NEWS

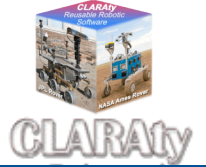
**CLARAty ROBOTIC SOFTWARE**

Welcome to the CLARAty website. This website contains information about the CLARAty reusable robotic software framework, videos of the capabilities that were demonstrated using CLARAty on real and simulated robotic platforms, and information on how to download and run the software. Also included on this site is information on the development team and contributors who provided algorithms and infrastructure since CLARAty's inception. We are grateful to the numerous contributions from this community as well as for the support of the Mars Technology Program and other NASA programs.



**CLARAty layers**

CLARAty stands for Coupled-Layer Architecture for Robotic Autonomy. It is a framework that promotes reusable robotic software. It was designed to support robotic software on heterogeneous robotic platforms and integrate advanced robotic capabilities from multiple institutions. Consequently, its design had to be portable, modular, flexible, and extendable.



*Thank you*